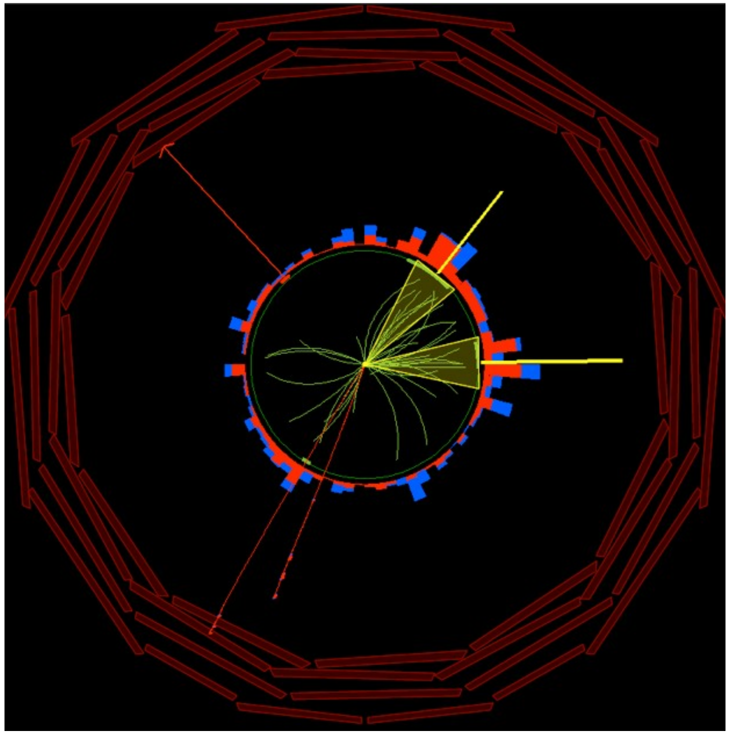
First LHC Results: High pT

Klaus Rabbertz
Institut für Experimentelle Kernphysik
Universität Karlsruhe

Karlsruhe Institute of Technology

The Menu

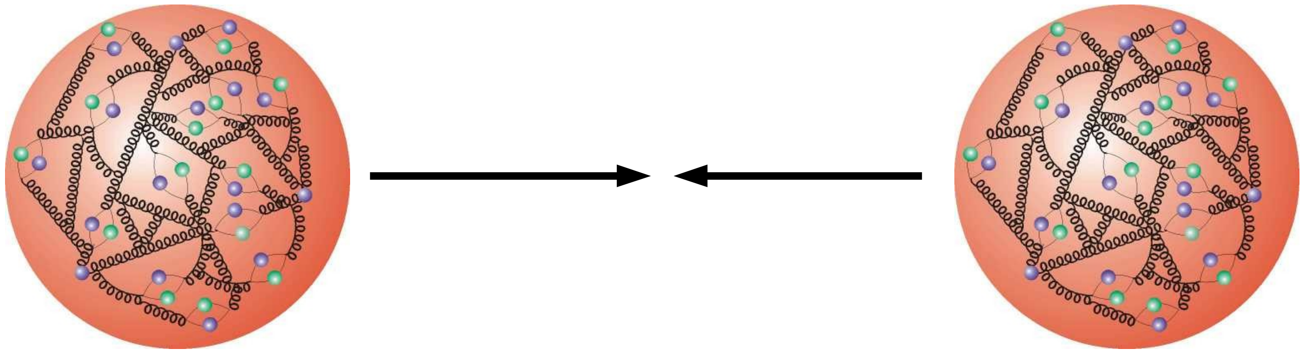
- One LHC
- A lot of Jets
- Numerous Photons
- Some W and Z Bosons
- A handful of Top
- Outlook



Unless noted otherwise all results are taken from ICHEP conference contributions:
Complete references can be found here:
ICHEP 2010 web page: http://www.ichep2010.fr
ATLAS public results web page:
https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
CMS public results web page:
https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

Apologies to ALICE and LHCb, I did not find much (yet) that fits into the high pT category … :-(

Luminosity



HERA-Proton,DESY

Expected Event Rates at LHC

Total cross section

Assuming here: L = 10^{30}cm^{-2}s^{-1}

Jets: $\sigma_{jet}(E_T^{jet} > 100\text{GeV})$ or

Photons: $\sigma_\gamma(E_T^\gamma > 20\text{GeV})$

~ 24 / min

W & Z bosons: σ_W, σ_Z

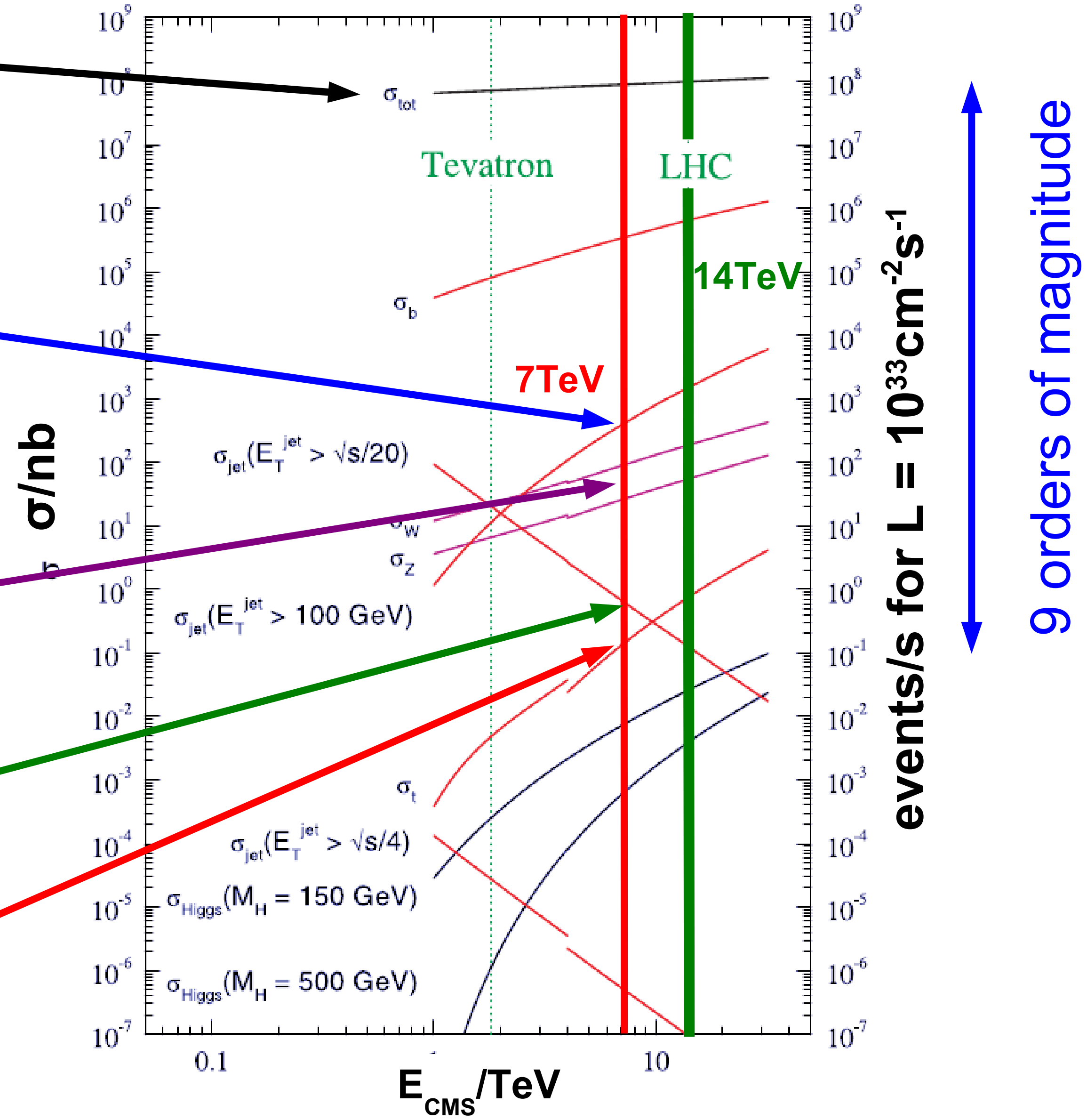
~ 6 / min, 2 / min

Jets: $\sigma_{jet}(E_T^{jet} > 350\text{GeV})$

~ 2 / hour

Top quarks (σ_{tt})

~ 9 / day



Delivered Luminosity

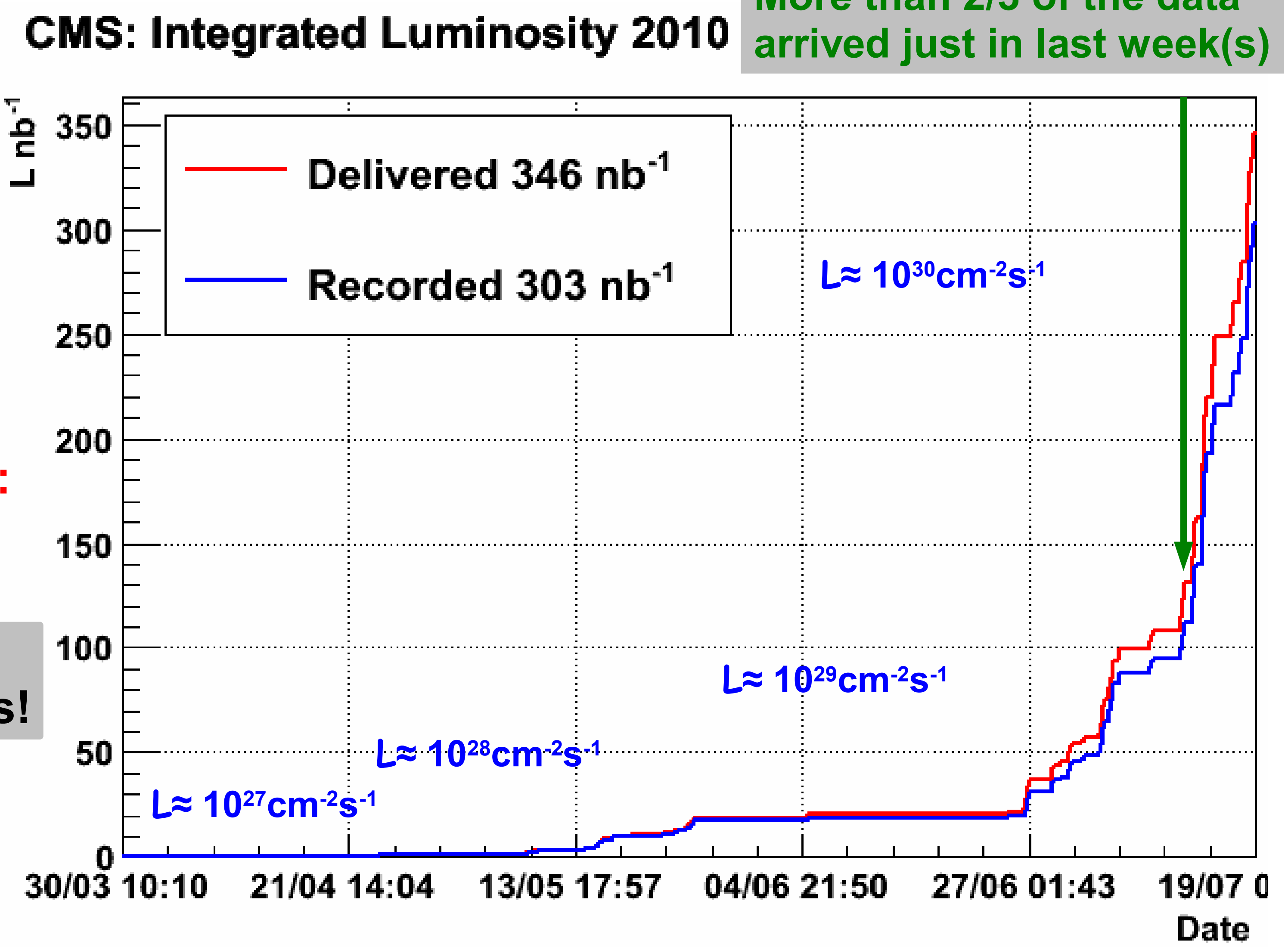
- <u>Instantaneous luminosity at LHC:</u>
  - Range since start-up: $L = 10^{27} – 10^{30}\ cm^{-2}s^{-1}$

Thousandfold increase!

  - Peak: $L = 1.6 \times 10^{30}\ cm^{-2}s^{-1}$
  - Luminosity uncertainty: ~ 11 %

Common uncertainty for all cross section measurements!

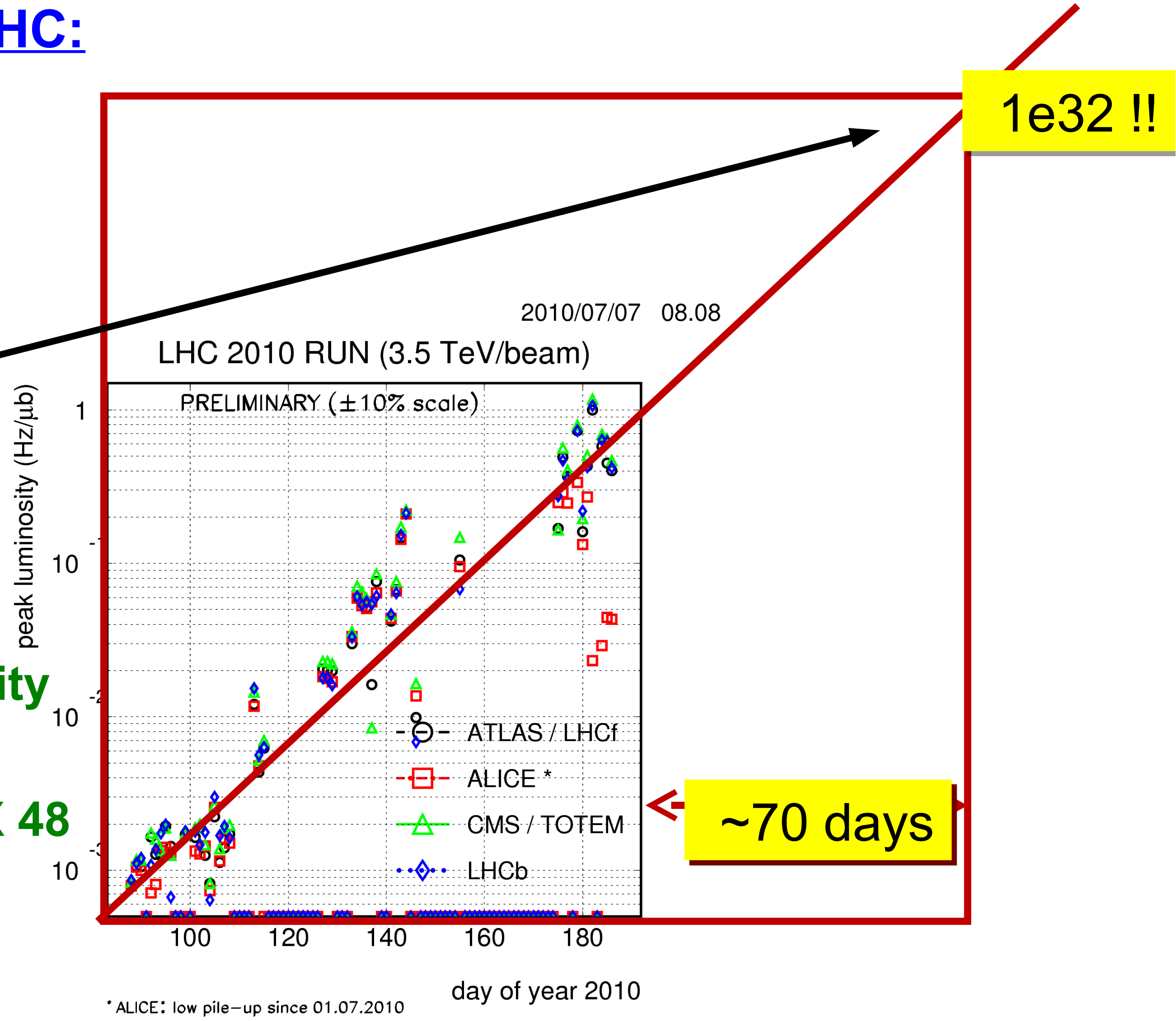
More than 2/3 of the data arrived just in last week(s)



Short Term Plan

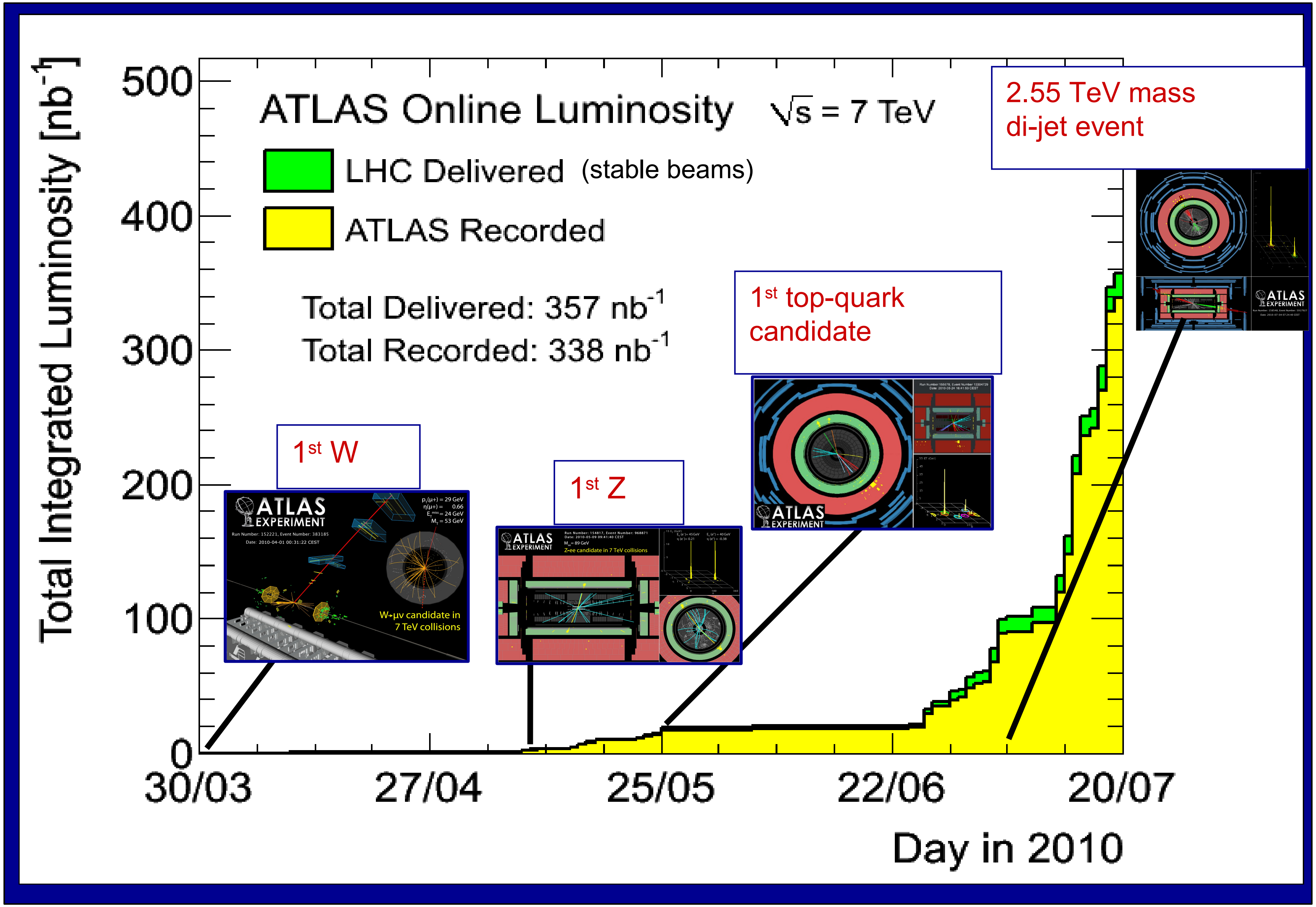
- **Instantaneous luminosity at LHC:**
  - **Range since start-up:**
    $L = 10^{27} - 10^{30}\ cm^{-2}s^{-1}$

Further increase by two orders of magnitude!

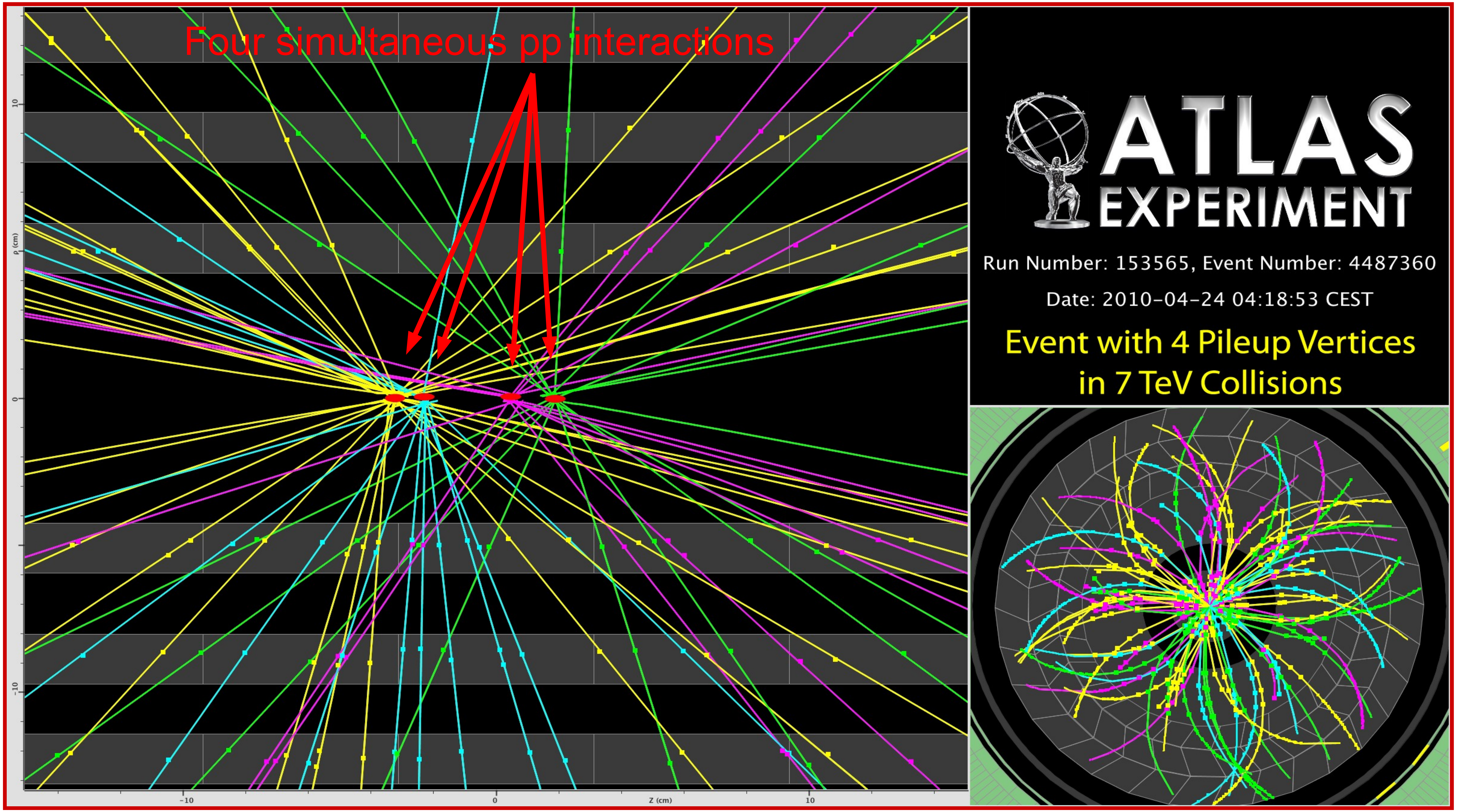


  - **Next steps:**
  - **Deliver 100 / nb of int. luminosity per day for 2 – 4 weeks**
  - **Commission running with 48 X 48 bunches (32 colliding)**

ATLAS Event (Hi)Story



Attention: Pile-up Events



Some Numbers

Note: Analyzed integrated luminosity and candidate selections vary between analyses and experiments!

Photons: $\sigma_\gamma(E_T^\gamma > 20\text{GeV})$
~ 24 / min

Highest photon pT: ATLAS: 150 GeV
CMS: ~ 200 GeV

W & Z bosons: σ_W, σ_Z
~ 6 / min, 2 / min

W candidate events: ATLAS: O(10^3)
(e,μ) **CMS: O(10^3)**
Z candidate events: ATLAS: O(10^2)
(ee & μμ) **CMS: O(10^2)**

Jets: $\sigma_{jet}(E_T^{jet} > 350\text{GeV})$
~ 2 / hour

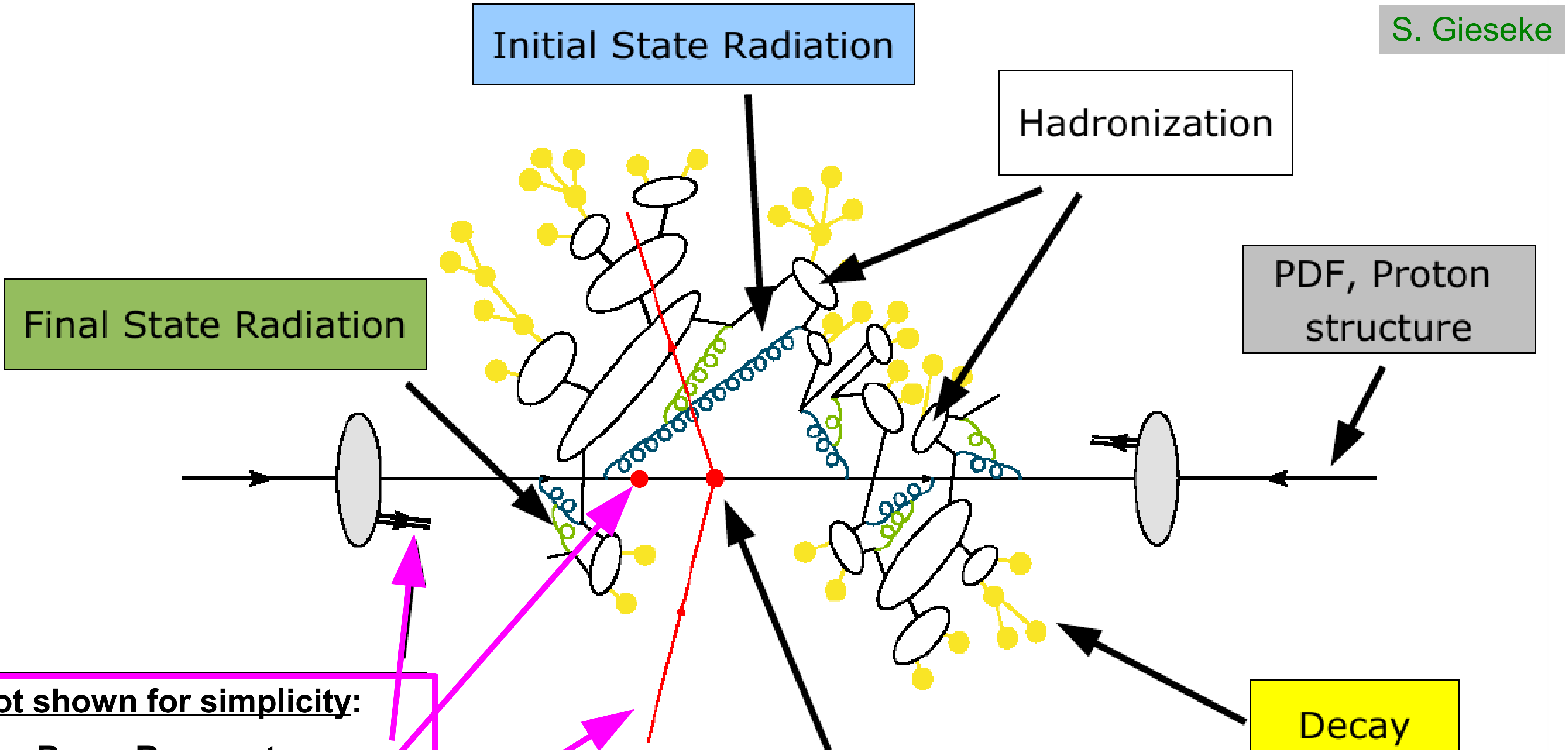
Highest jet pT: ATLAS: 1.12 TeV

Highest dijet mass: ATLAS: 2.55 TeV
CMS: 2.13 TeV

Top quarks (σ_{tt})
~ 9 / day

Top candidate events: ATLAS: 2+7 = 9
(dilepton & lepton+jets) **CMS: 2+3 = 5**

Sketch of a pp Scatter



Not shown for simplicity:

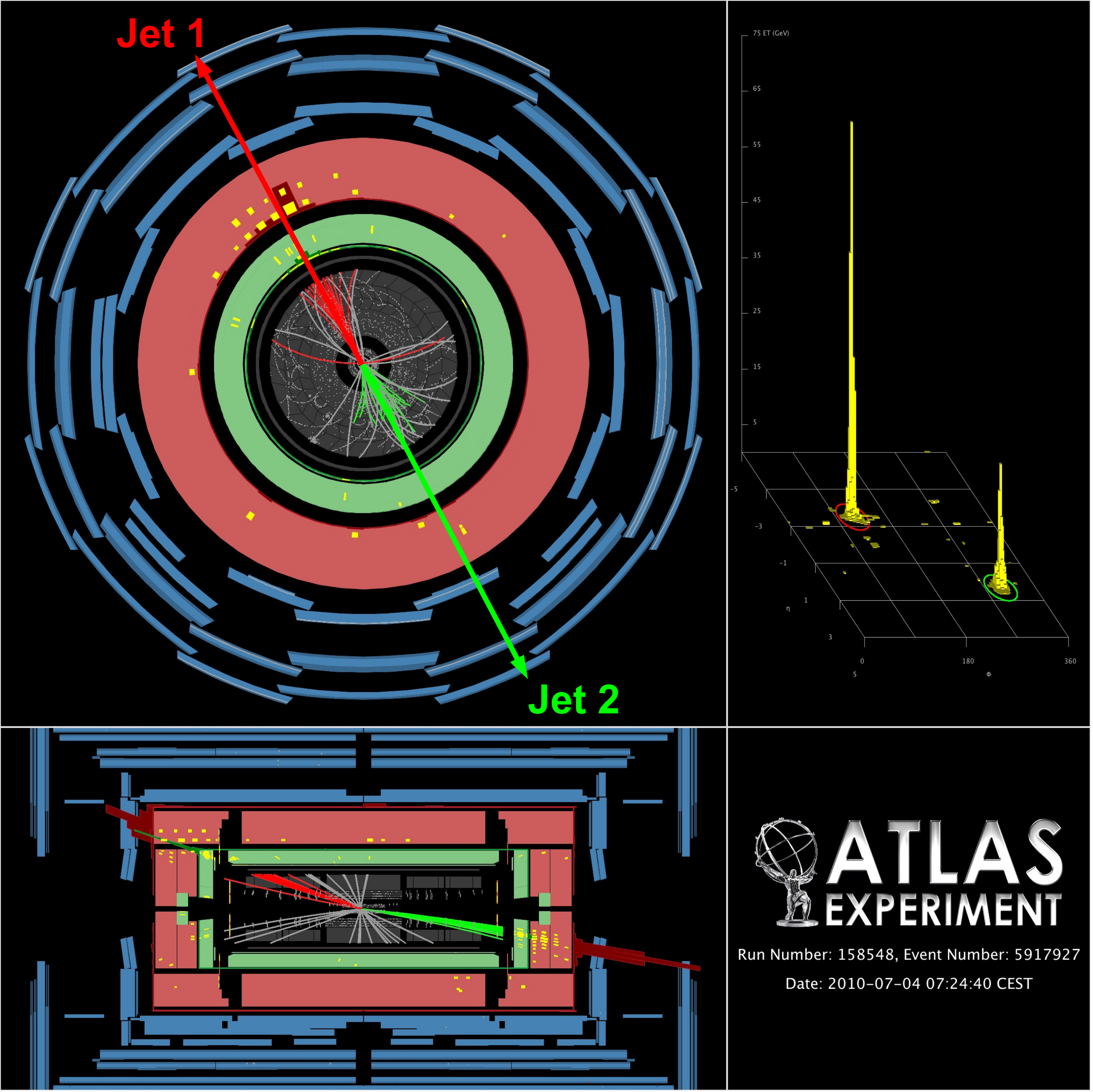
Beam Remnants

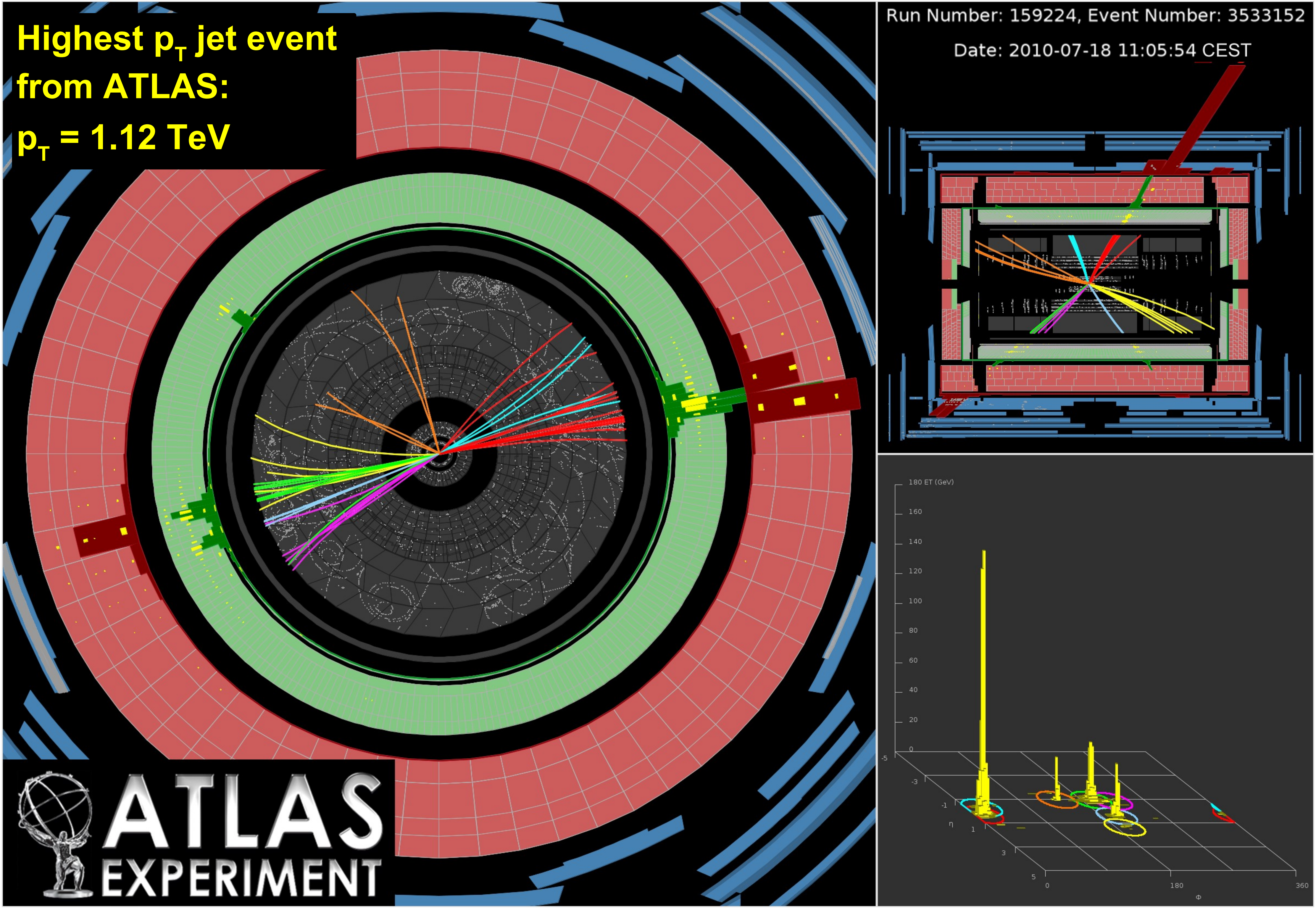
Multiple Interactions

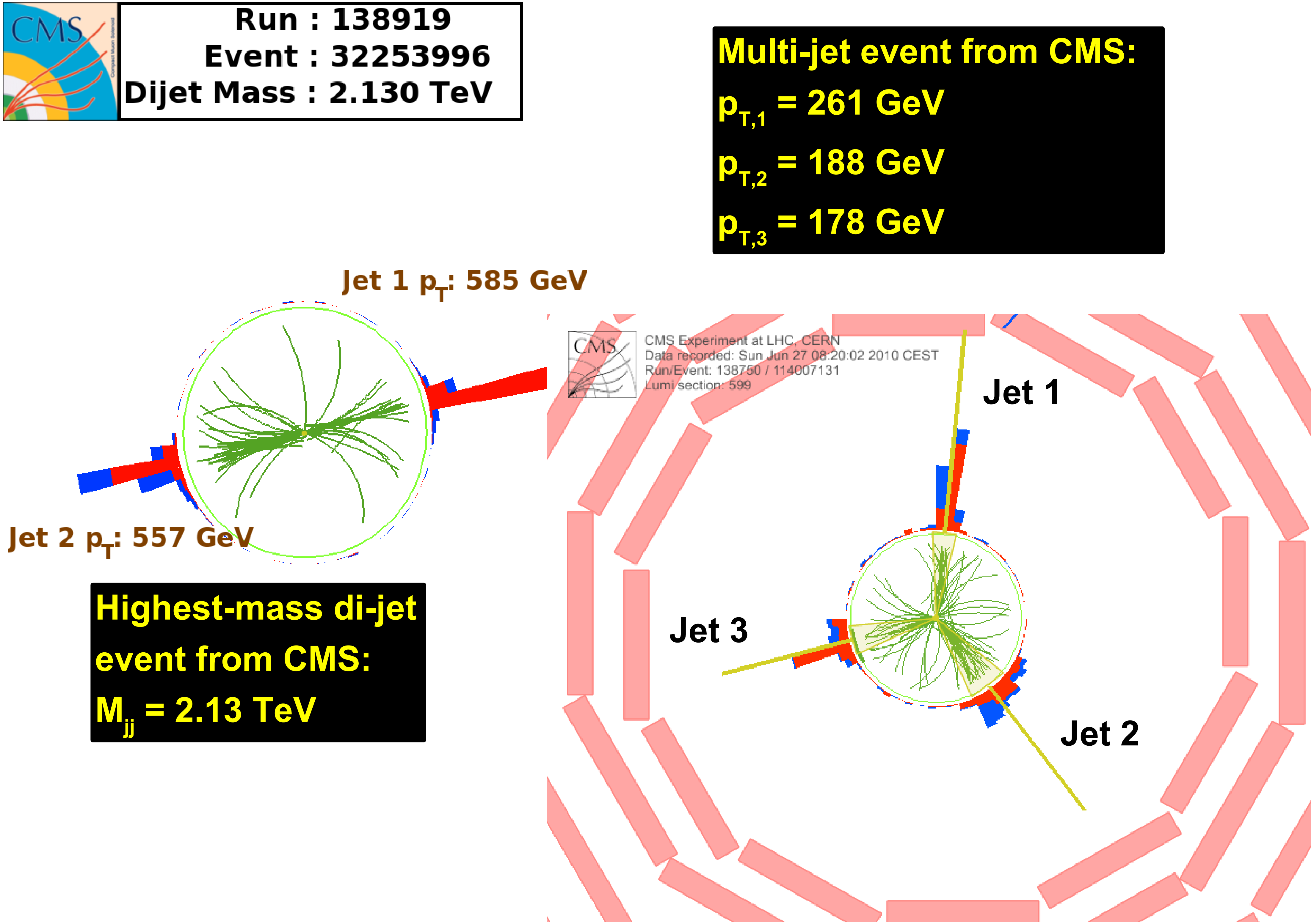
FSR off the hard partons

PLUS … a Detector!

Highest-mass di-jet event from ATLAS: M_{jj} = 2.55 TeV

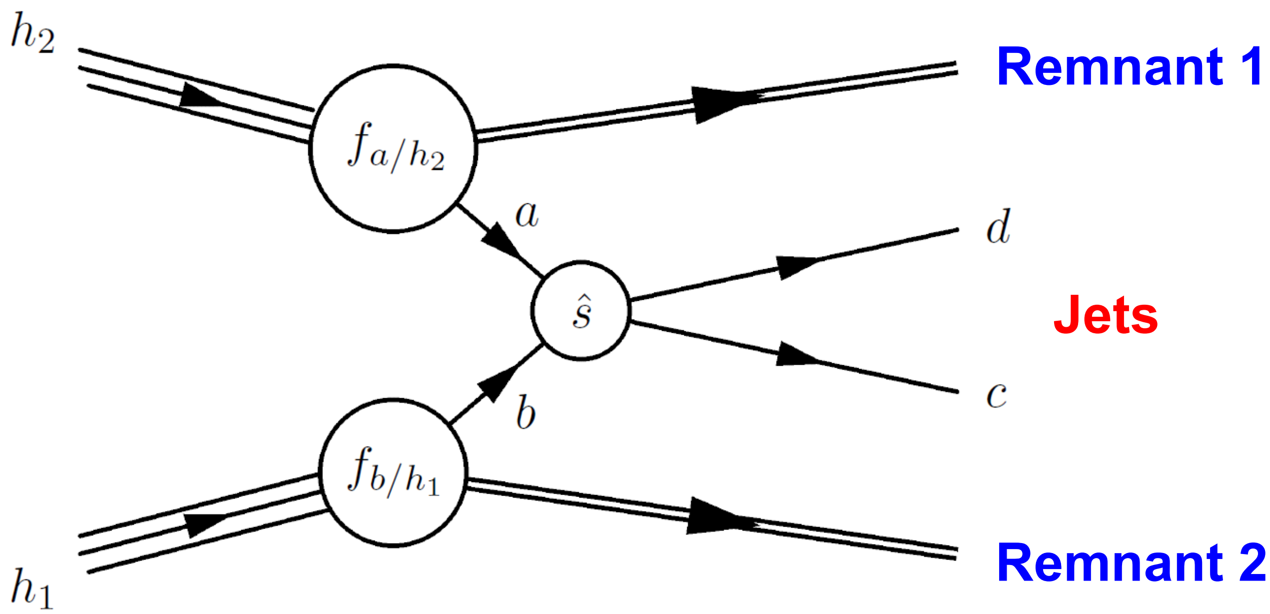



Highest p_T jet event from ATLAS:
p_T = 1.12 TeV
Run Number: 159224, Event Number: 3533152
Date: 2010-07-18 11:05:54 CEST
180 ET (GeV)
160
140
120
100
80
60
40
20
0
-5
-3
-1
η
1
3
5
0
180
360
Φ
ATLAS
EXPERIMENT


CMS
Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV
Multi-jet event from CMS:
$p_{T,1}$ = 261 GeV
$p_{T,2}$ = 188 GeV
$p_{T,3}$ = 178 GeV
Jet 1 p_T: 585 GeV
Jet 2 p_T: 557 GeV
Highest-mass di-jet event from CMS:
M_{jj} = 2.13 TeV
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 27 08:20:02 2010 CEST
Run/Event: 138750 / 114007131
Lumi section: 599
Jet 1
Jet 3
Jet 2

Jets

Lachlan Rogers, Wikimedia

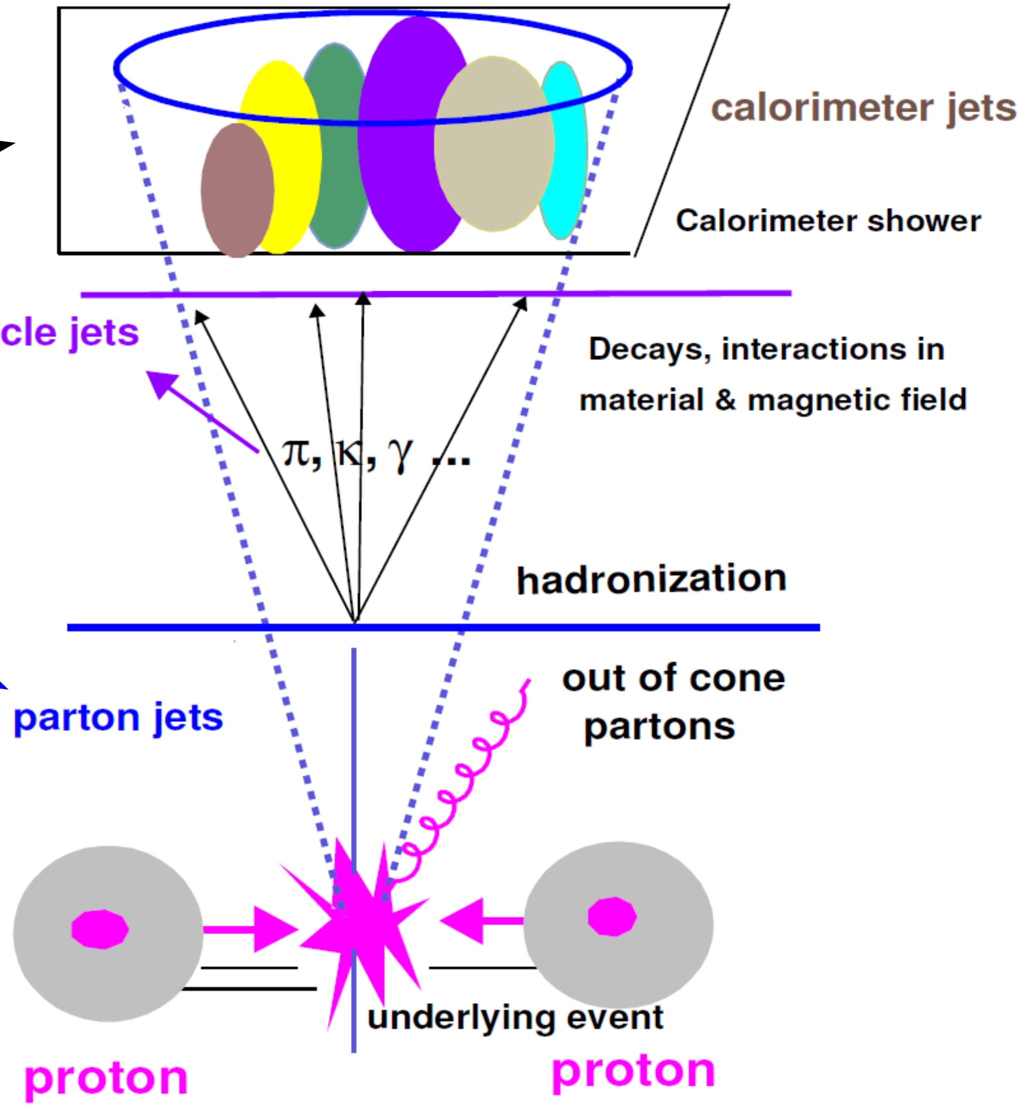


See also lectures from Kenichi Hatakeyama

Jet Algorithms 1/3

Primary Goal:

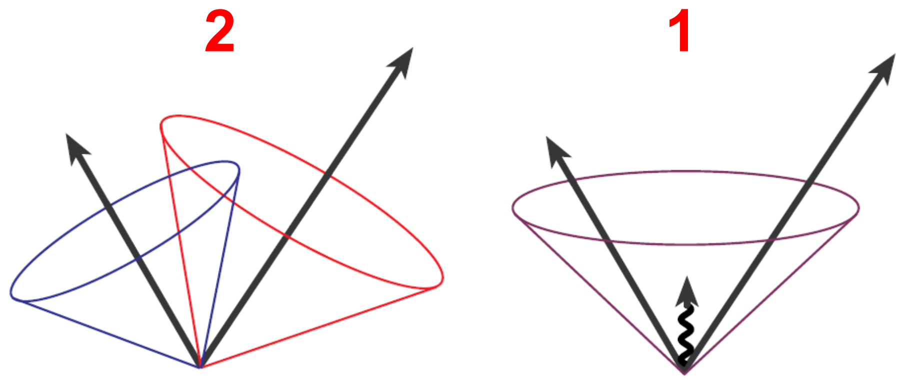
Establish a good correspondence between:
- detector measurements
- final state particles and
- hard partons



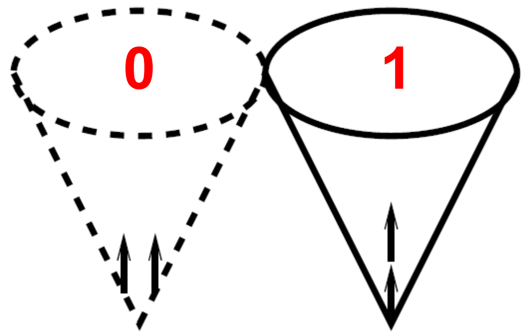
Two classes of algorithms:
- Cone algorithms: "Geometrically" assign objects to the leading energy flow objects in an event (favorite choice at hadron colliders)
- Sequential recombination: Repeatedly combine closest pairs of objects (favorite choice at e^+e^- & ep colliders)

Jet Algorithms 2/3

- **Jet Algorithm Desiderata (Theory):**
  - **Infrared safety**
  - **Collinear safety**
  - **Longitudinal boost invariance**
    (recombination scheme!)
  - **Boundary stability**
    (→ 4-vector addition, rapidity y)
  - **Order independence**
    (parton, particle, detector)
  - **Ease of implementation**
    (standardized public code?)



IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

"Snowmass Accord", FNAL-C-90-249-E
Tevatron Run II Jet Physics, hep-ex/0005012

Jet Algorithms 3/3

- **Jet Algorithm Desiderata (Experiment):**
  - **Computational efficiency and predictability**
    (use in trigger?, reconstruction times?)
  - **Maximal reconstruction efficiency**
  - **Minimal resolution smearing and angular biasing**
  - **Insensitivity to pile-up**
    (mult. collisions at high luminosity ...)
  - **Ease of calibration**
  - **Detector independence**
  - **Fully specified**
    (details?, code?)
  - **Ease of implementation**
    (standardized public code?)

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

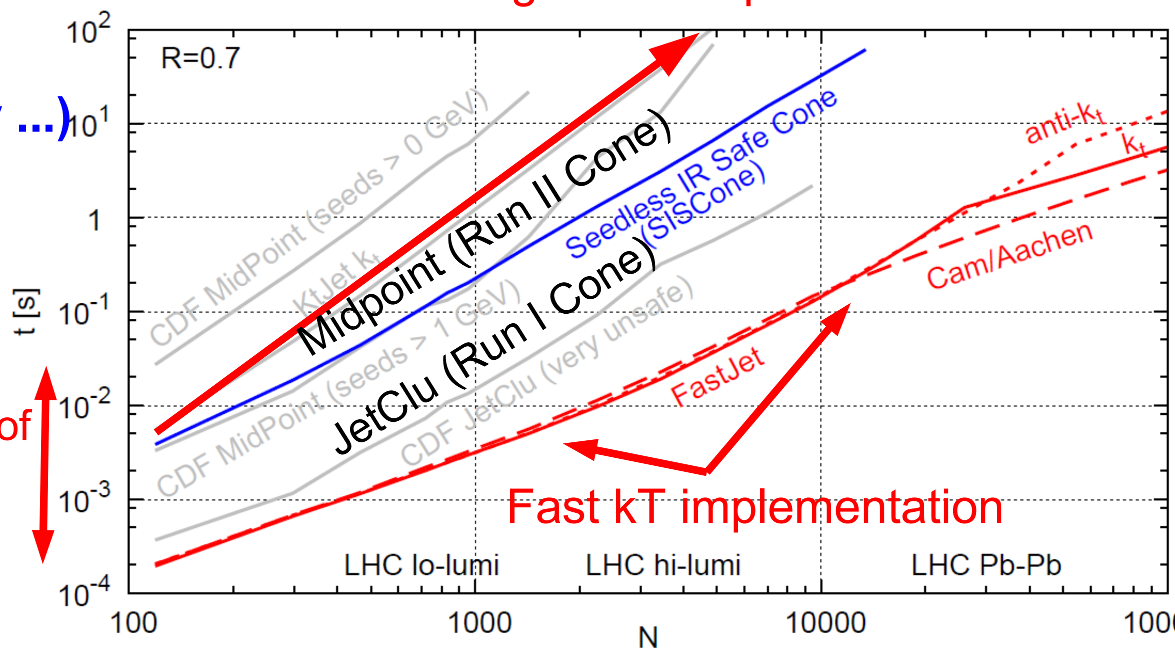
$$d_{iB} = k_{ti}^{2p} ,$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

p = 1: kT
p = 0: Cambridge/Aachen
p = -1: anti-kT

Original kT implementation

2-3 orders of magnitude



Fast kT implementation

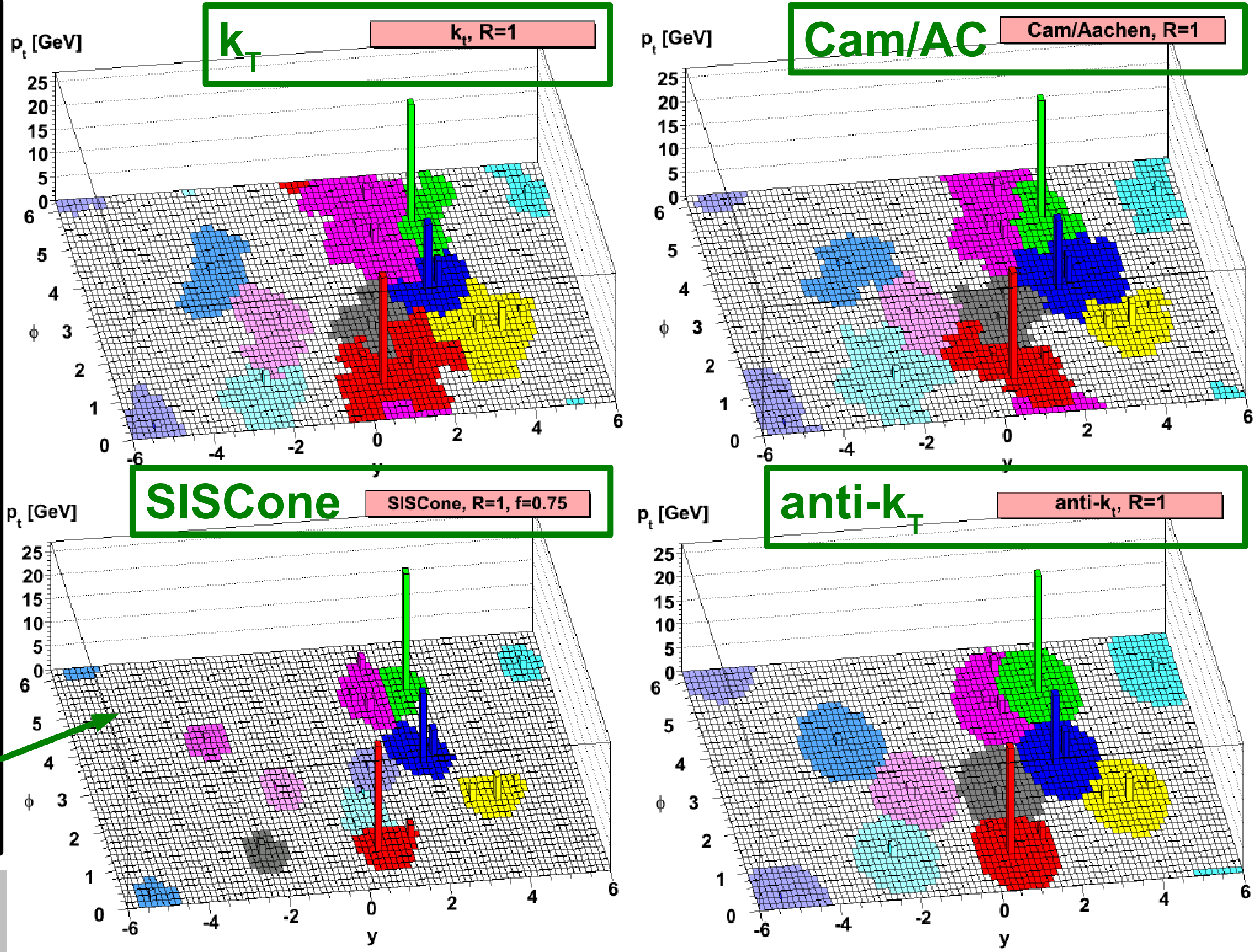
Jetography, G. Salam, hep-ph/0906.1833

Jet Algorithms at LHC

Primary algorithm at LHC:

- **Anti-k_T:**
  ATLAS R = 0.4, 0.6
  CMS R = 0.5, 0.7
- k_T: R = 0.4, 0.6 (ATLAS & CMS)
- SISCone: R = 0.5, 0.7 (CMS)
- Cambridge/Aachen used in jet substructure, for example in boosted top

General interest to work with all four



Fast kT, Cacciari/Salam, PLB641, 2006
SISCone, Salam/Soyez, JHEP05, 2007
anti-kT, Cacciari et al., JHEP04, 2008

Jet Measurements

All jets in the event satisfying the selection criteria

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\epsilon \cdot L \cdot \Delta p_T \cdot \Delta y} \times C_{unsm}$$

Master Equation

- Jet Efficiency
- Event Efficiency

Bins of **corrected** Jet Pt and Jet rapidity

Unsmearing correction (due to the finite detector Pt resolution)

Luminosity, common uncertainty to all measurements

The JES dominates the total uncertainty of the measurement

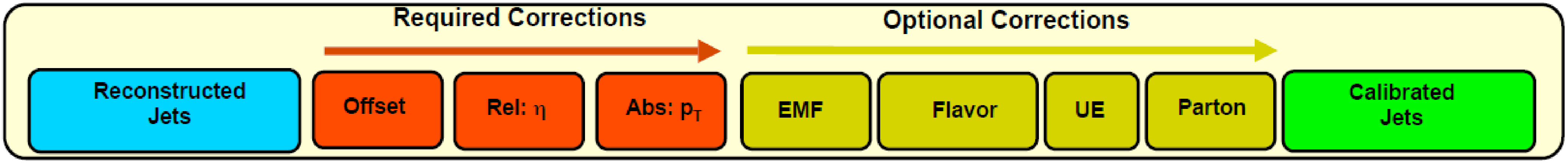
K. Kousouris

Jet Analysis Uncertainties

- **Experimental Uncertainties (~ in order of importance):**
  - Jet Energy Scale (JES)
    - Noise Treatment
    - Pile-Up Treatment
  - Luminosity
  - Jet Energy Resolution (JER)
  - Trigger Efficiencies
  - Resolution in Rapidity
  - Resolution in Azimuth
  - Non-Collision Background
  - • • •

- **Theoretical Uncertainties (~ in order of importance):**
  - PDF Uncertainty
  - pQCD (Scale) Uncertainty
  - Non-perturbative Corrections
  - PDF Parameterization
  - Electroweak Corrections
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

Jet Energy Calibration



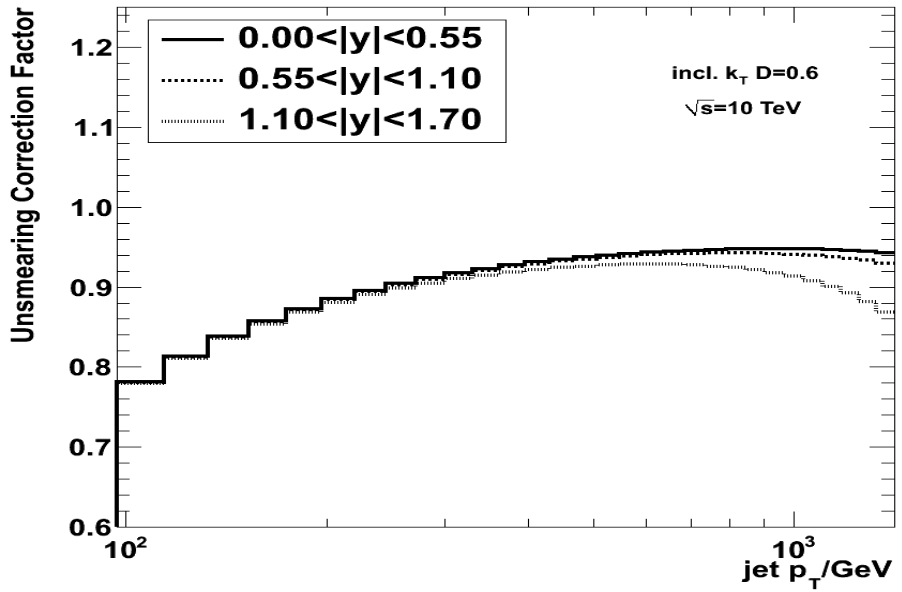
à la CMS

- **Offset:** Correct for detector noise and pile-up
  (use random triggers = zero bias, special read-out for noise)
- **Relative (η):** Equalize jet response in η w.r.t. control region (barrel)
  (dijet balancing; or MC)
- **Absolute (p_T):** Correct measured jet p_T to particle jet p_T
  (photon + 1jet, Z + 1jet events)
- **Optional analysis dependent corrections:** Electromagnetic fraction, flavour, … will not discuss here
- Initial assumption on JEC uncertainty: CMS Calorimeter: 10%
  ATLAS lAr Calo: 7%
  CMS Calo&Tracks: 5%

Resolution Unsmearing Steps

Motivation

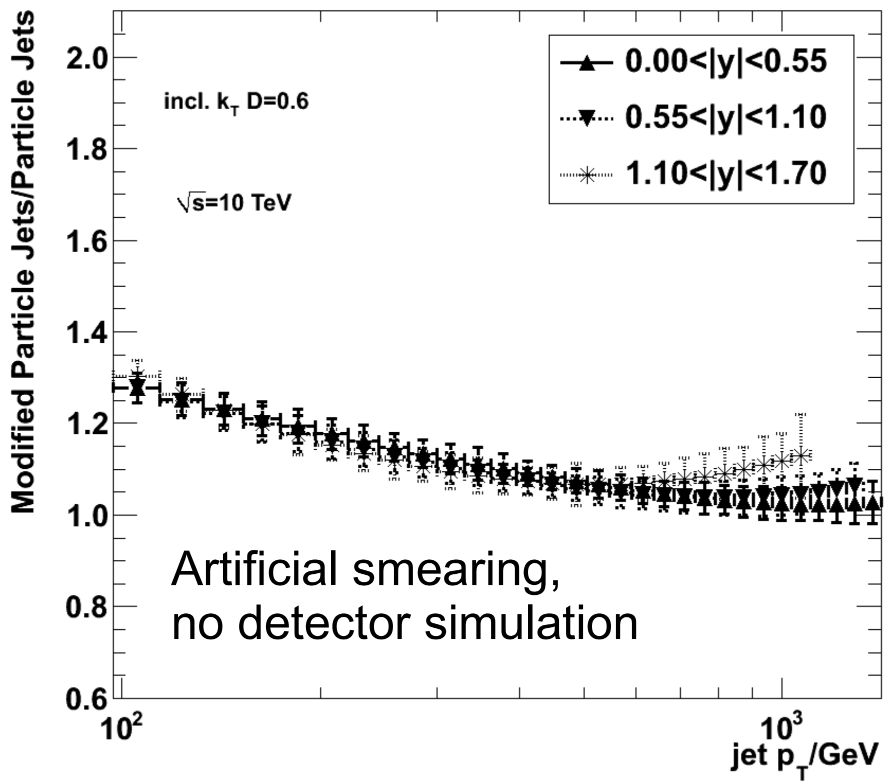
The **observed** cross section is **higher** than the true one due to the falling shape of the spectrum and the finite p_T resolution. More events migrate into a bin of measured p_T than out of it.



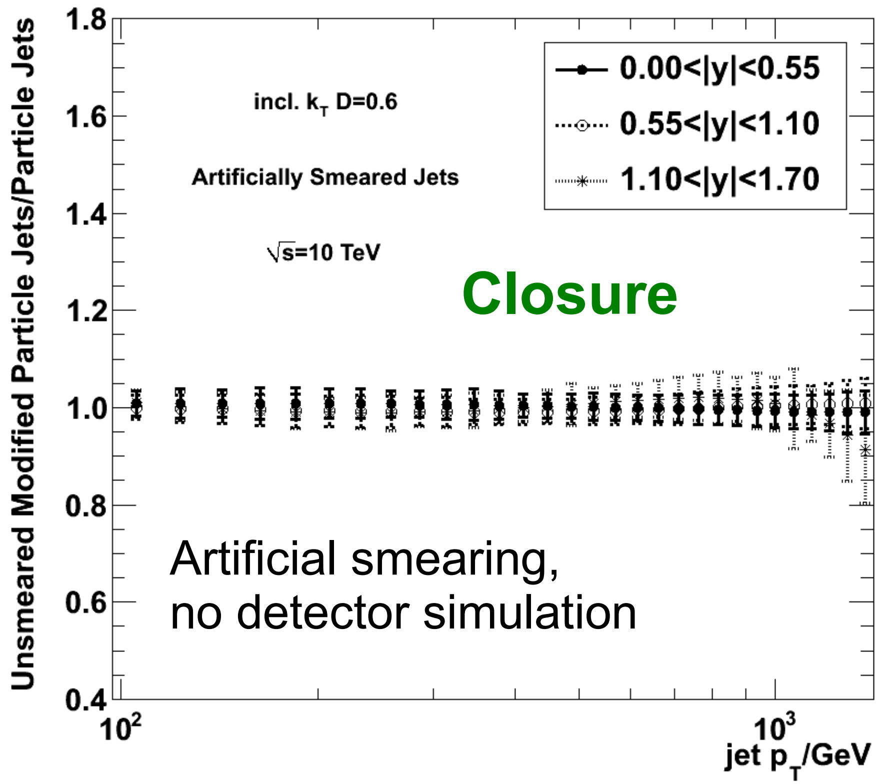
Unsmearing steps:

- Analytical expression of the p_T resolution ➡ $$R(p'_T, p_T) = \frac{1}{\sqrt{2\pi}\sigma(p'_T)} \exp\left[-\frac{(p'_T - p_T)^2}{2\sigma^2(p'_T)}\right]$$
- Ansatz function with free parameters to be determined by the data ➡ $$f(p_T) = N \cdot p_T^{-a} \cdot \left(1 - \frac{2\cosh(y_{min})p_T}{\sqrt{s}}\right)^b \exp(-\gamma p_T)$$
- Fitting the data with the Ansatz function smeared with p_T resolution. ➡ $$F(p_T) = \int_0^\infty f(p'_T) R(p'_T, p_T) dp'_T$$
- Unsmearing correction calculated bin by bin. ➡ $$C_{bin} = \frac{\int_{bin} f(p_T) dp_T}{\int_{bin} F(p_T) dp_T}$$

Unsmearing Applied



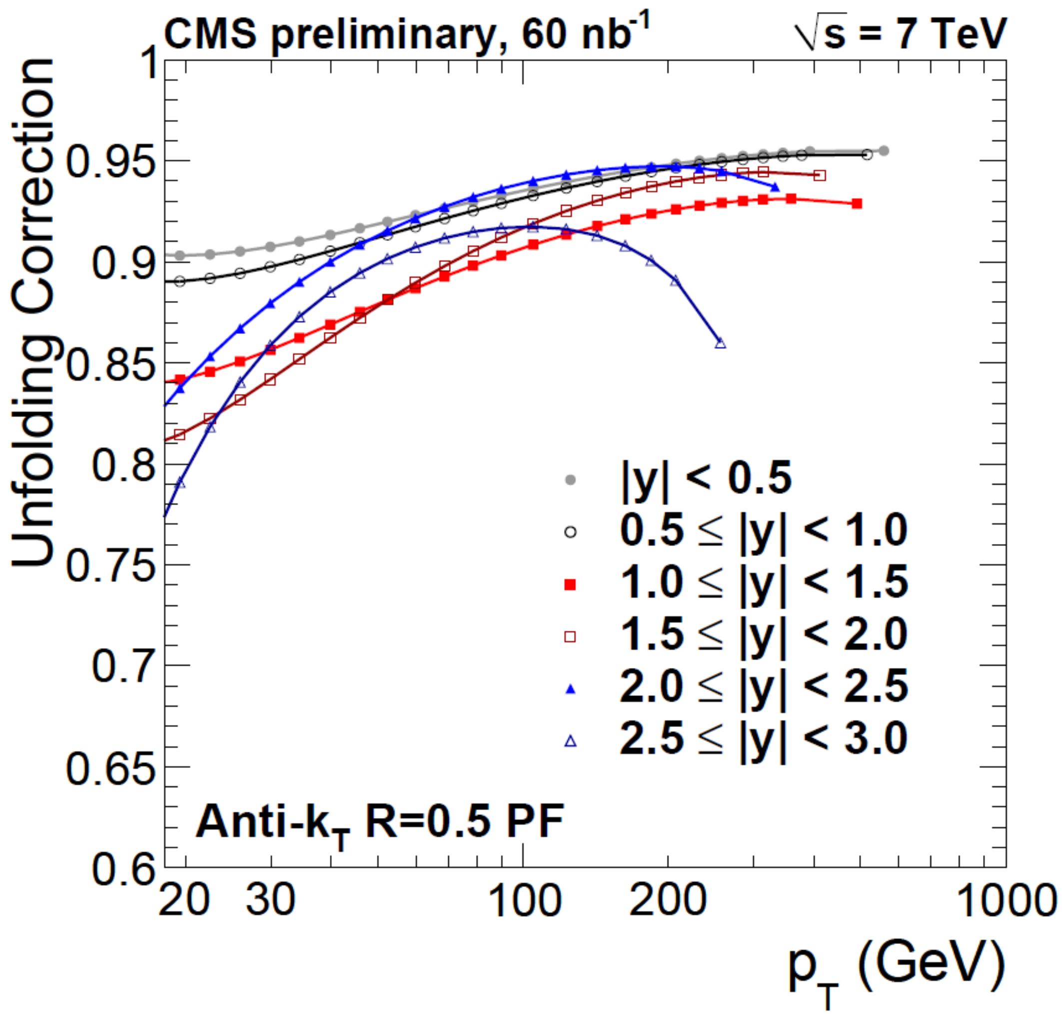
Unsmearing by "Ansatz Method"



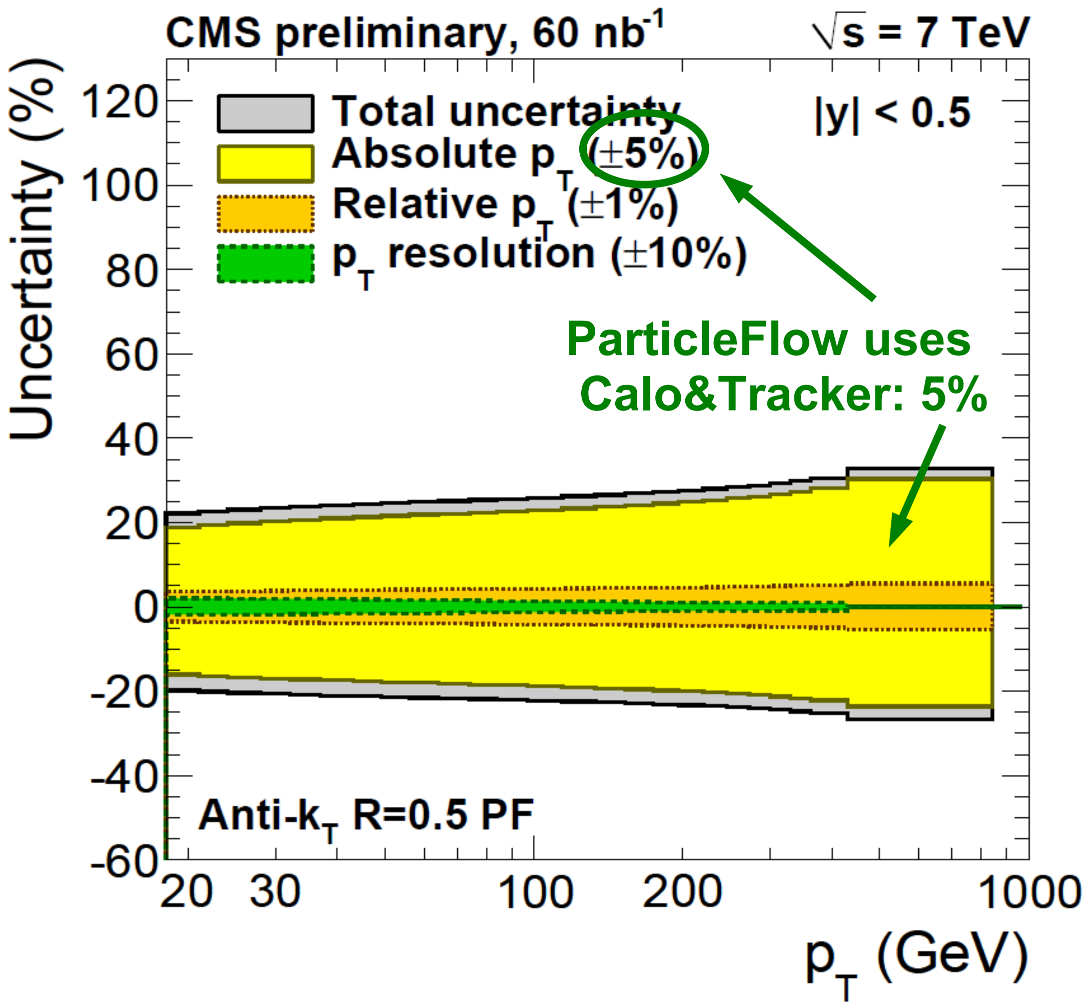
- Artificially smear jets by Gaussian with an arbitrary but reasonable p_T dependent width.
- Apply ansatz method
- Method corrects p_T smearing effects on steeply falling spectrum

Incl. Jet pT: Exp. Uncertainties

Correction for Jet Energy Resolution



Dominant: Absolute jet energy scale

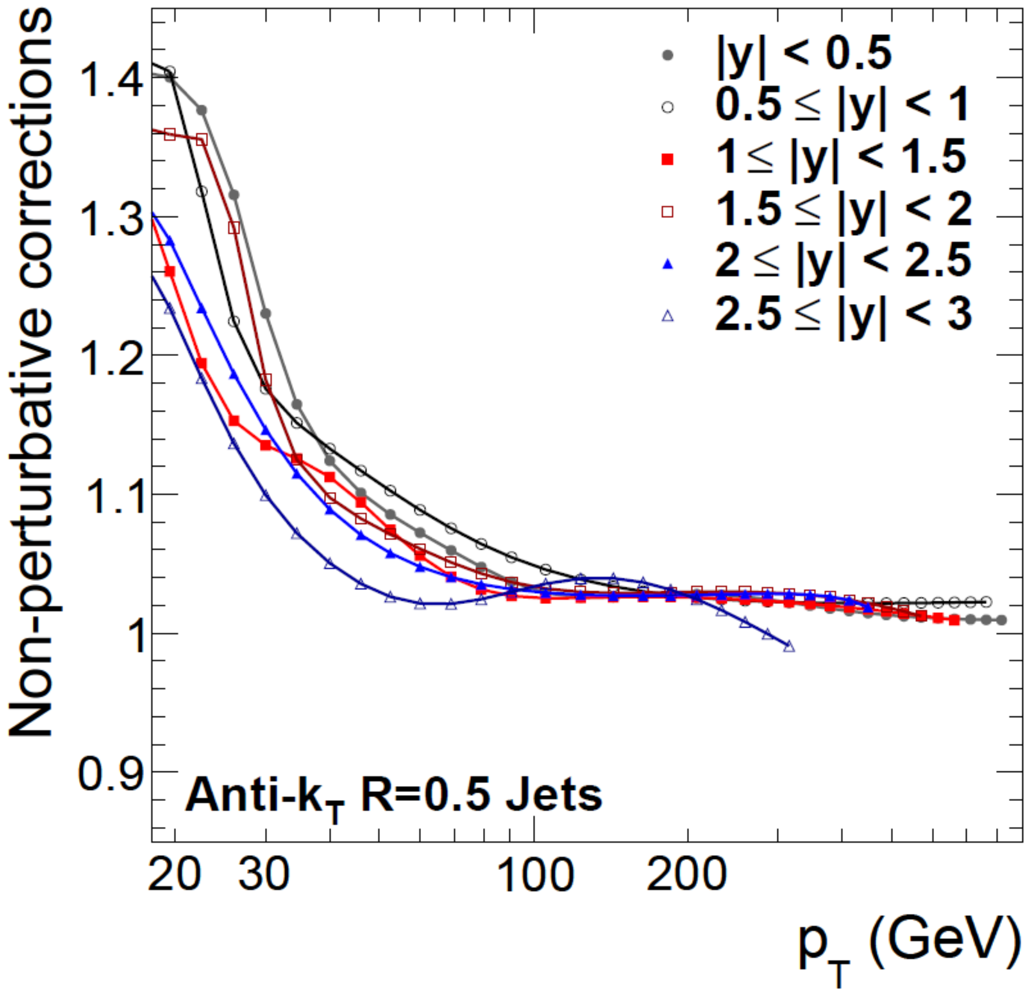


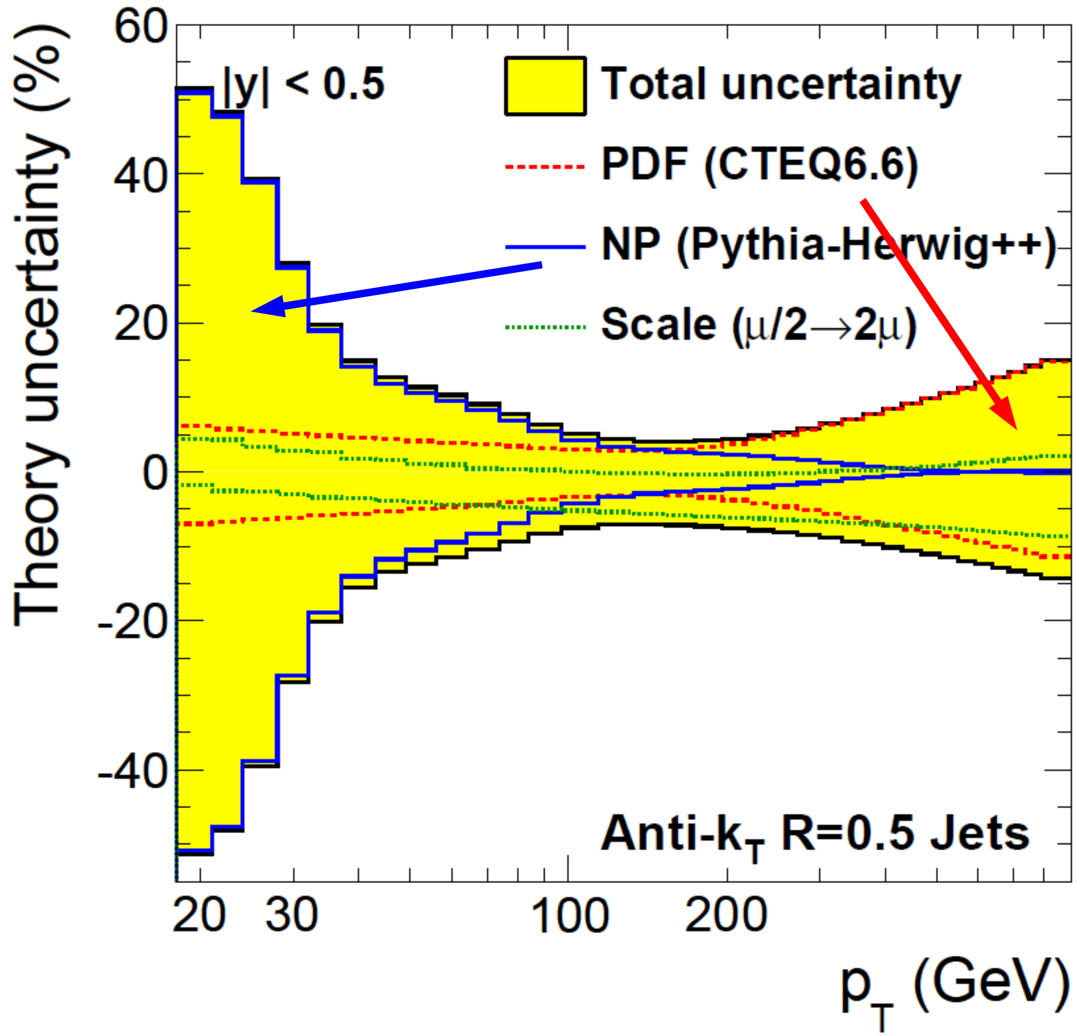
Incl. Jet pT: Theory Uncertainties

To compare with data correct NLO for:

- Multiple Parton Interactions (MPI)
- Hadronization & Decays (Lund, Cluster)

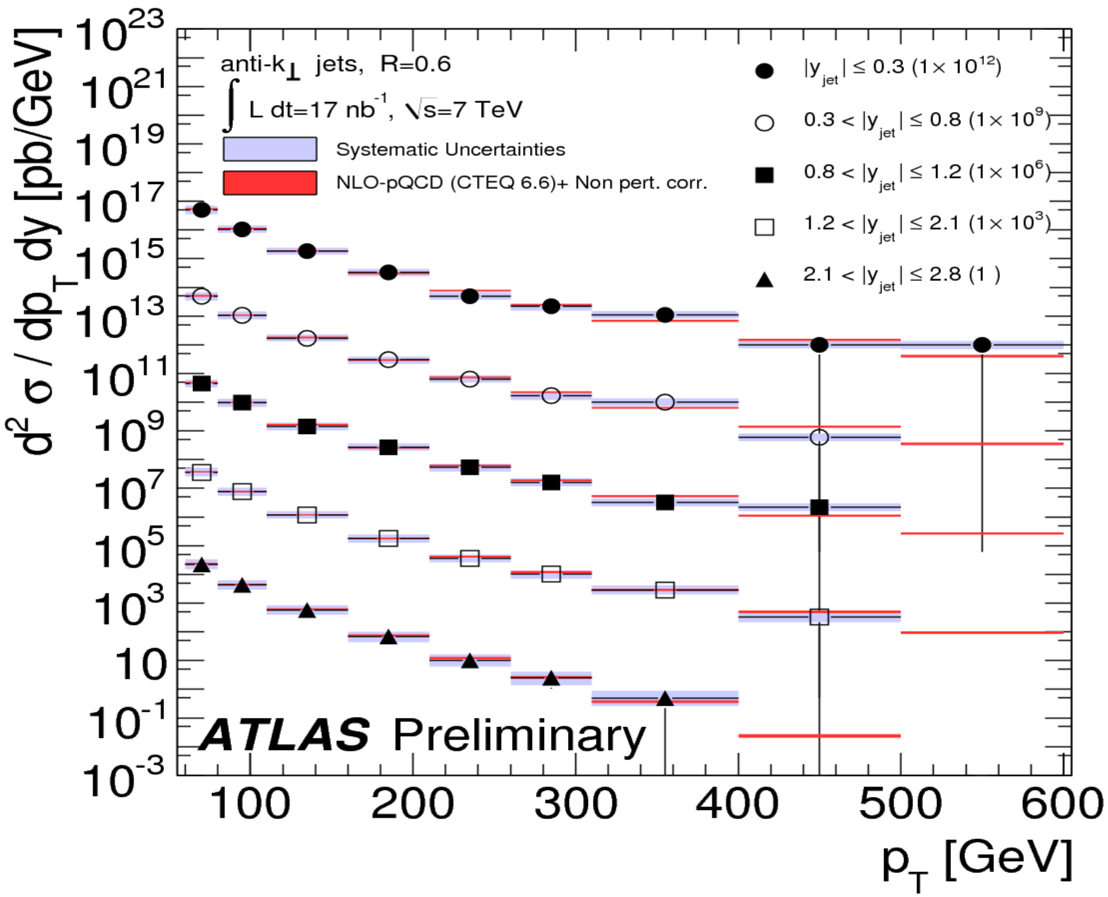
Dominant at low pT: np. Corrections
at high pT: PDF

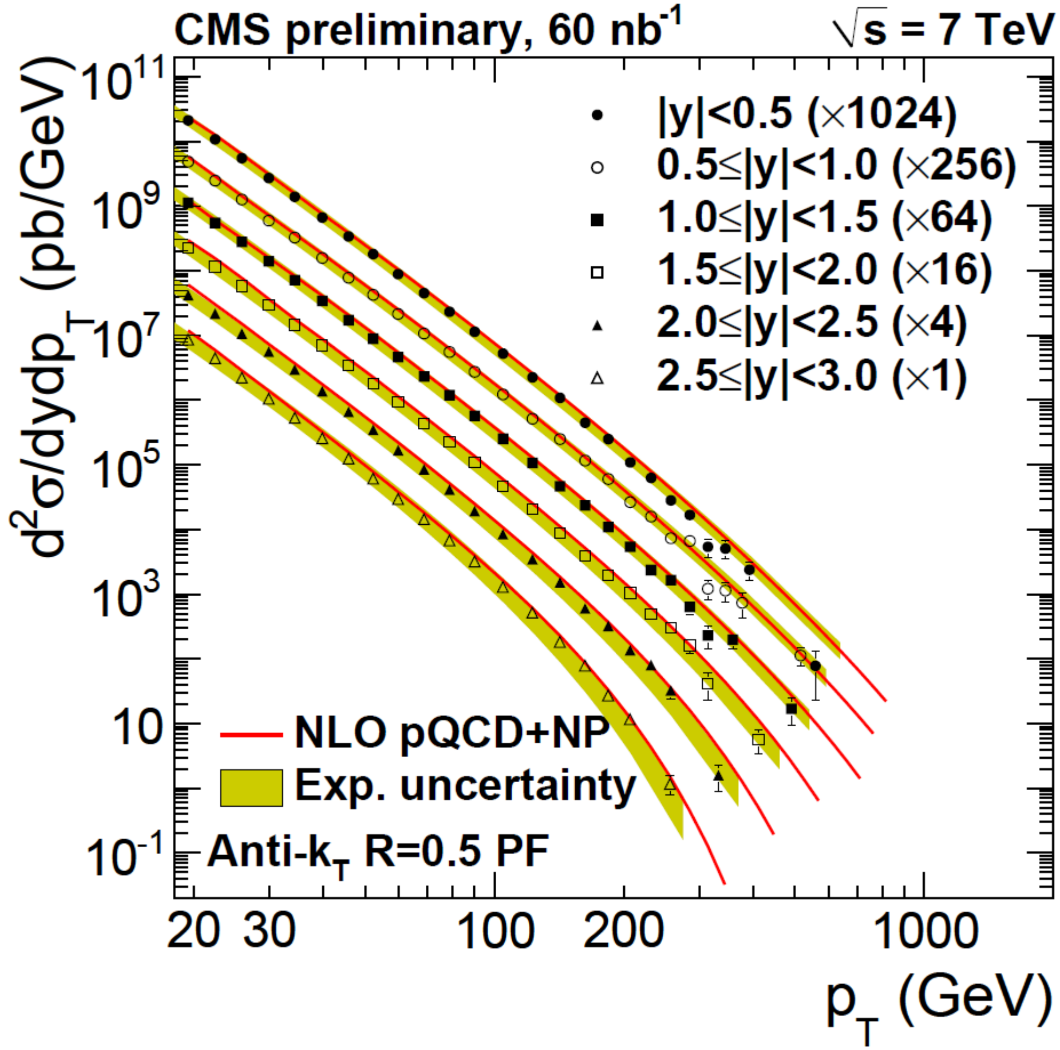




Incl. Jet pT: Cross Section

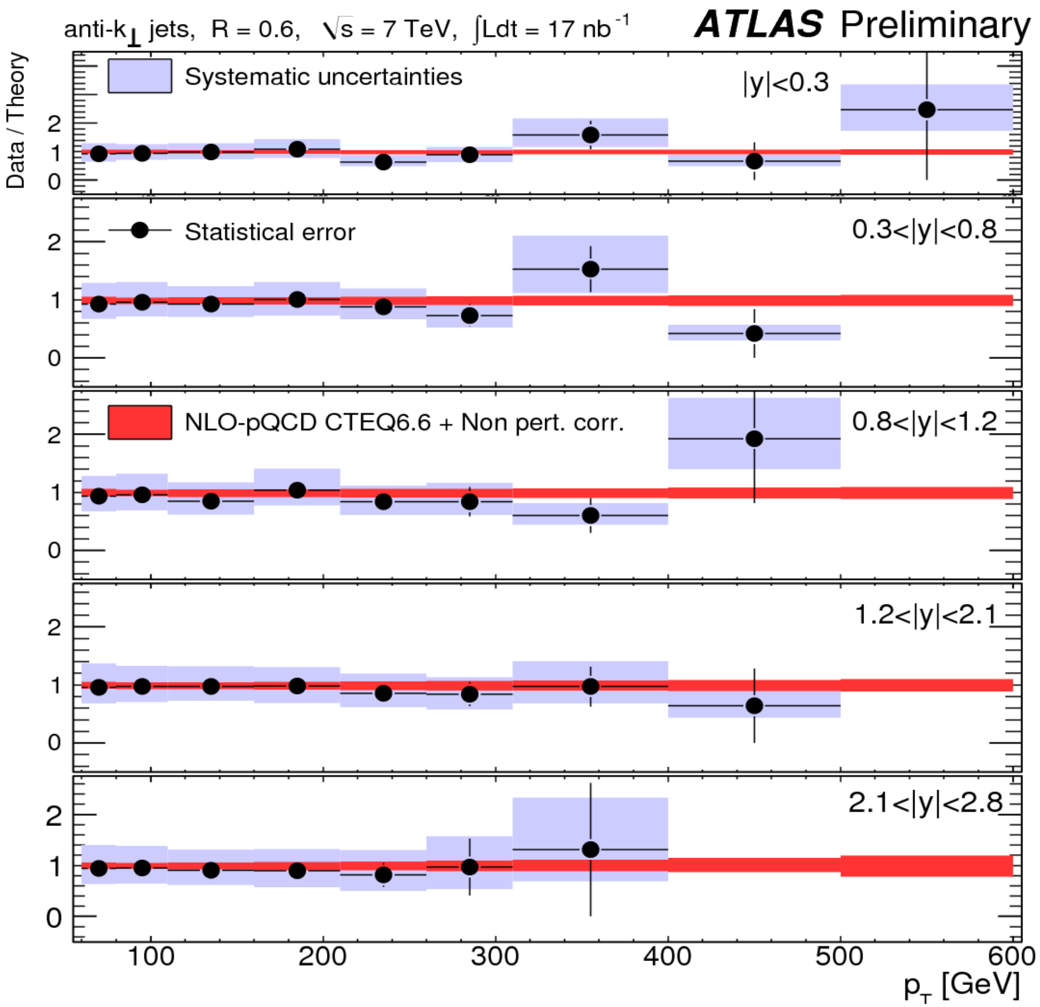
Measurements mostly below QCD predictions, compatible within uncertainties.

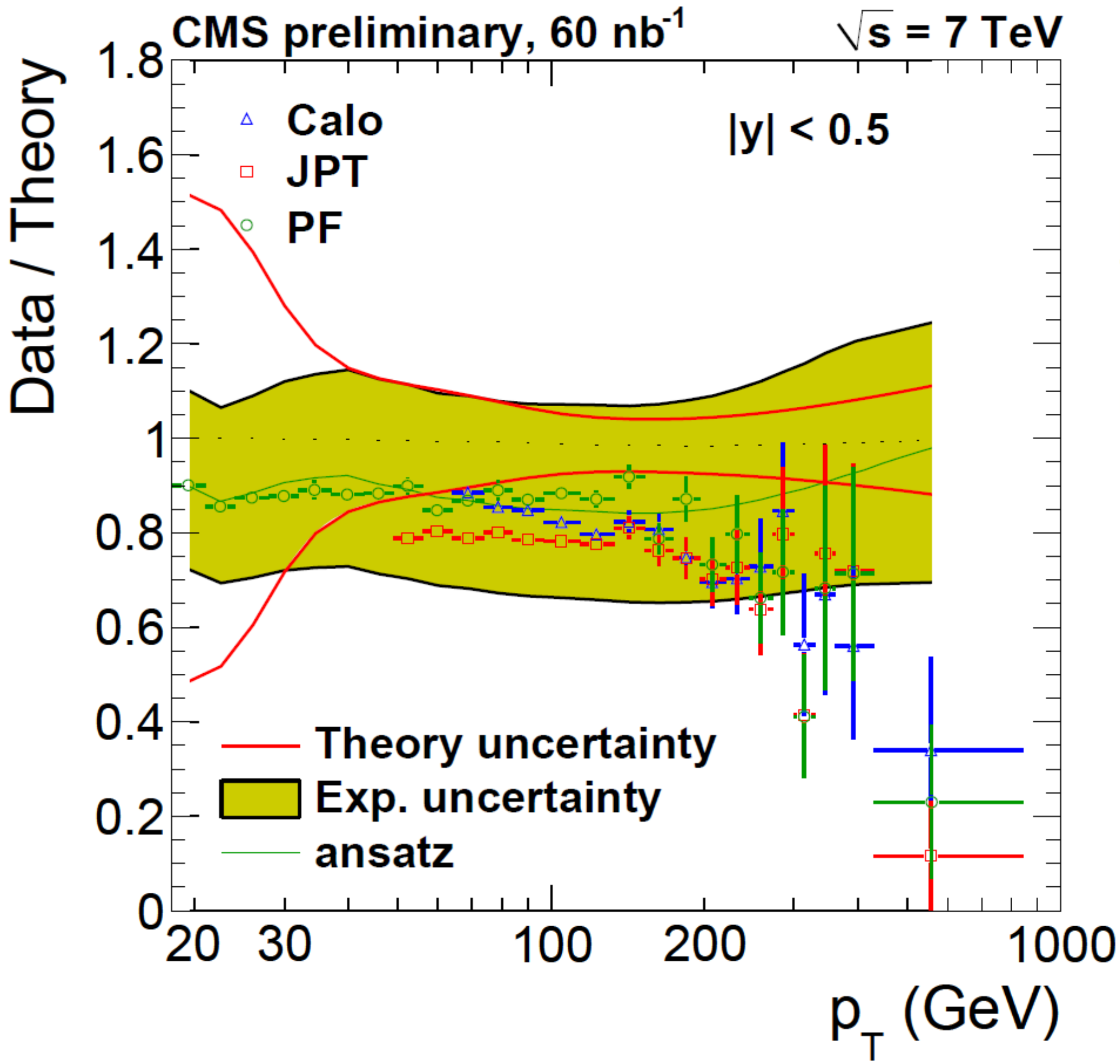




Incl. Jet pT: Data / Theory

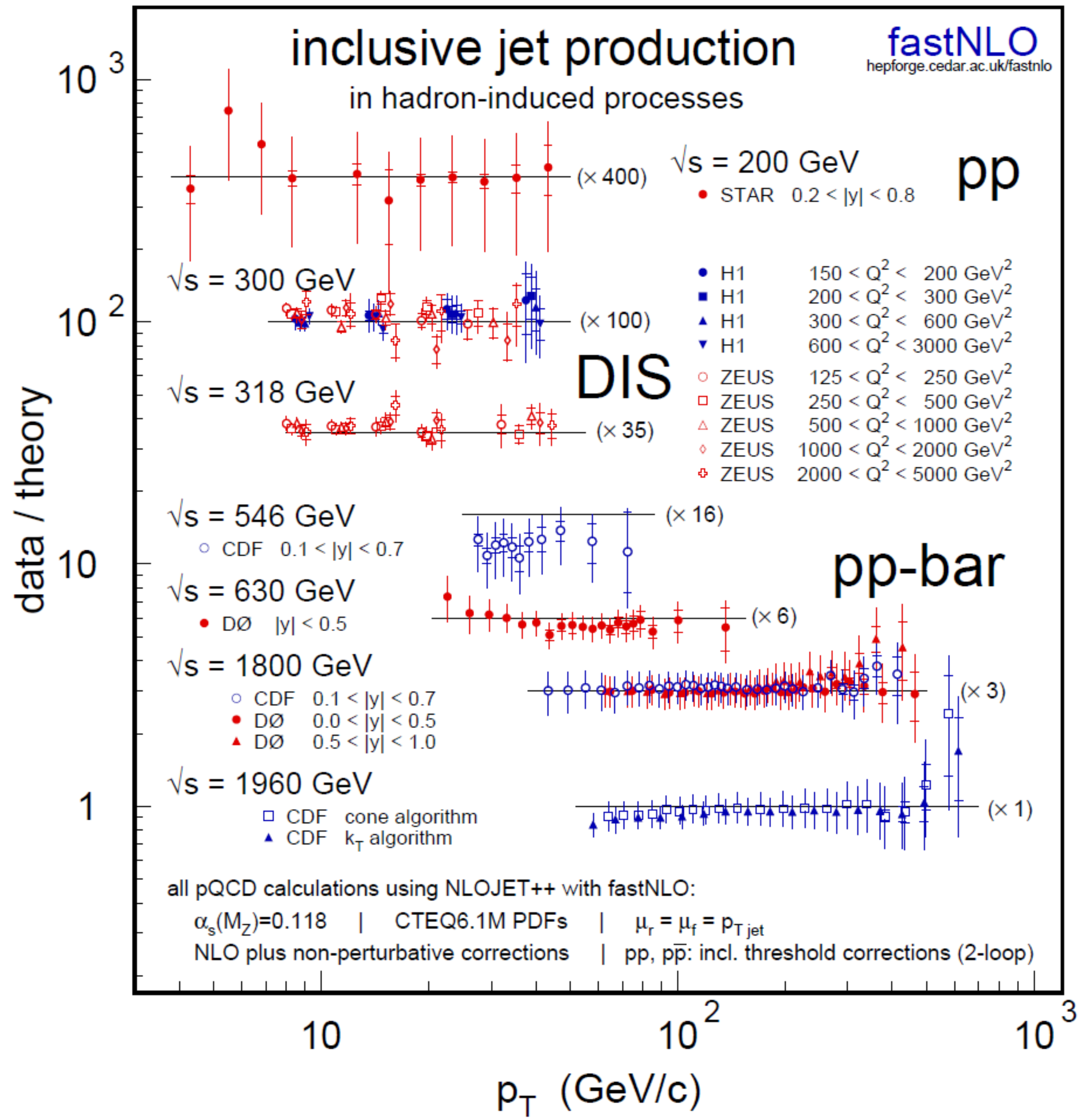
Compatible within uncertainties!





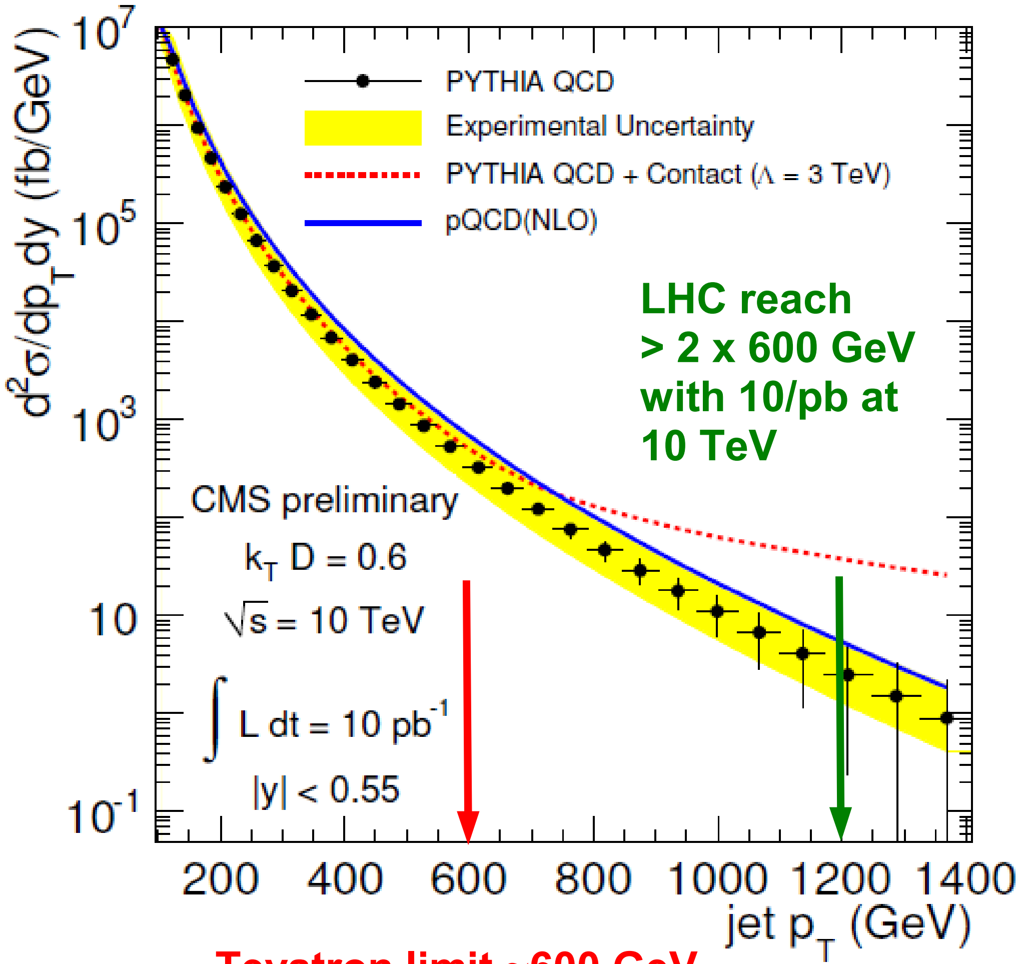
Previous Jets Data / Theory

- Comparison of jet data from
  - STAR at RHIC
  - H1 and ZEUS at HERA
  - CDF and D0 at Tevatron
- Compatible with NLO pQCD

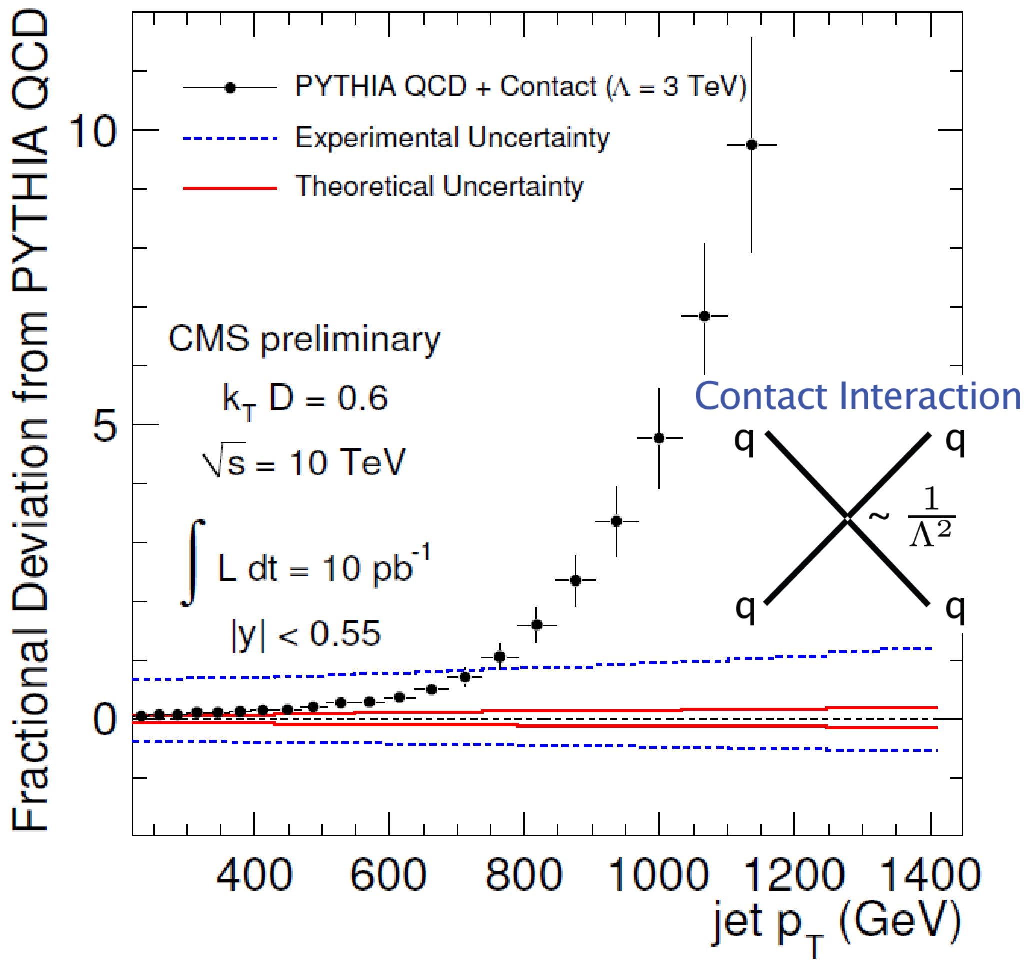


Simulation: Contact Interactions

k_T, D=0.6, 10 TeV — Comparison with Contact Interactions



Tevatron limit ~600 GeV
LHC ICHEP ~600 GeV

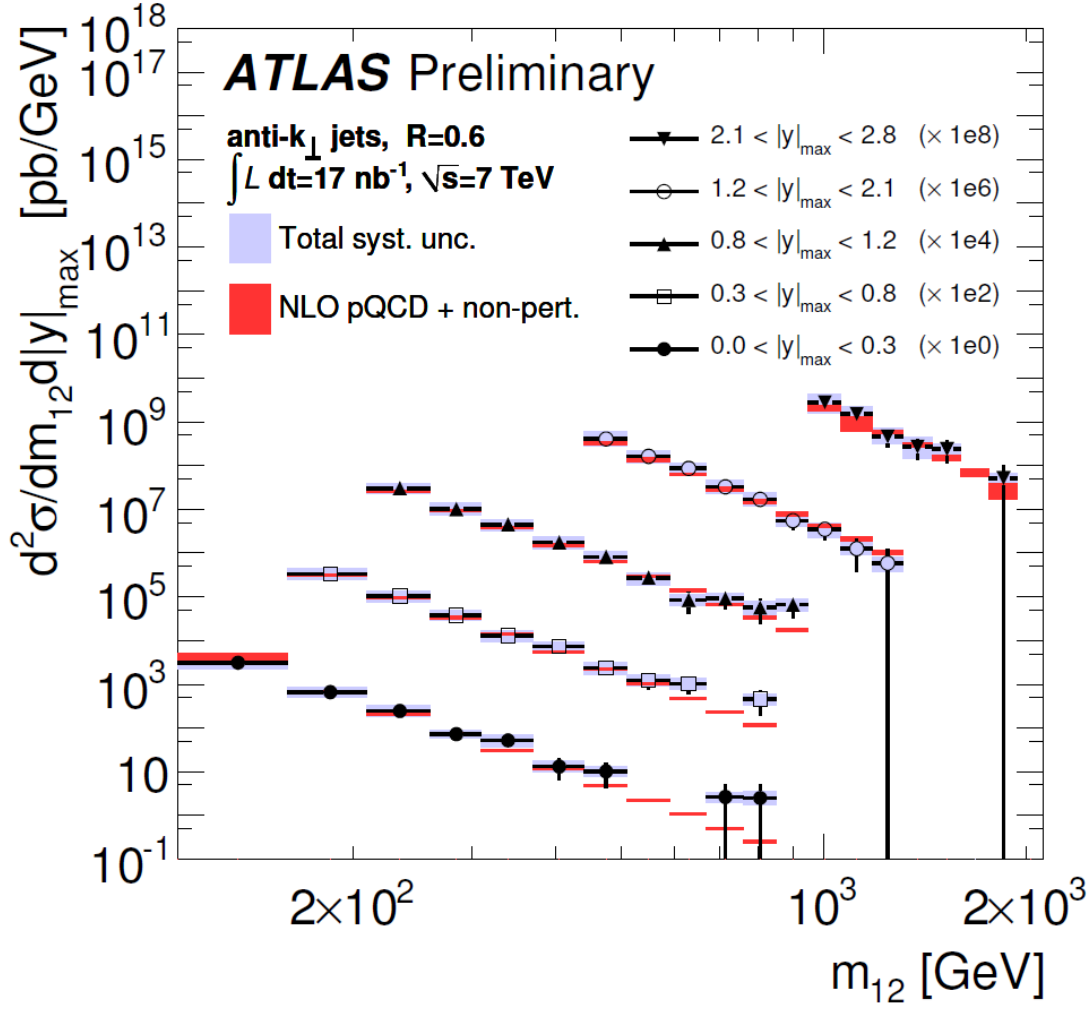


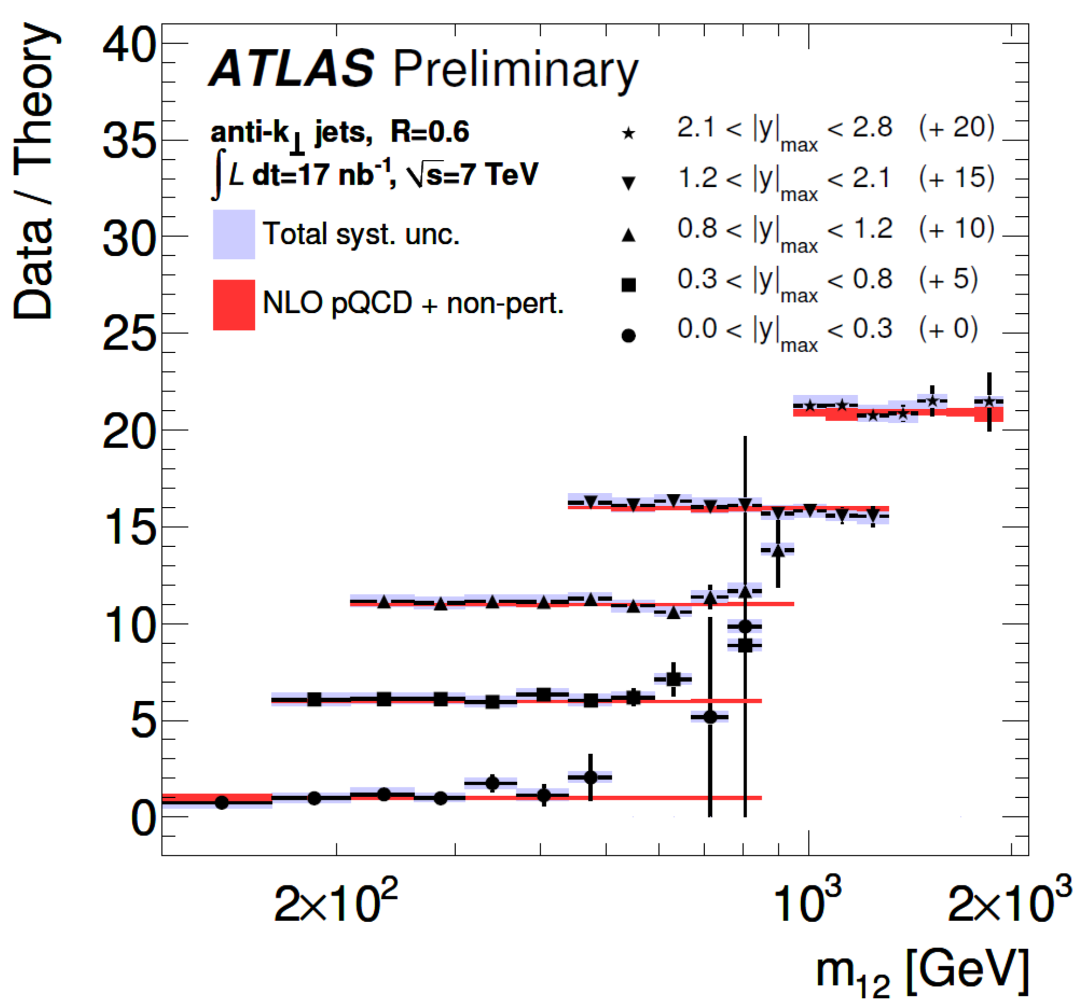
CMS PAS QCD-08-001

Dijet Mass

Compatible within uncertainties!

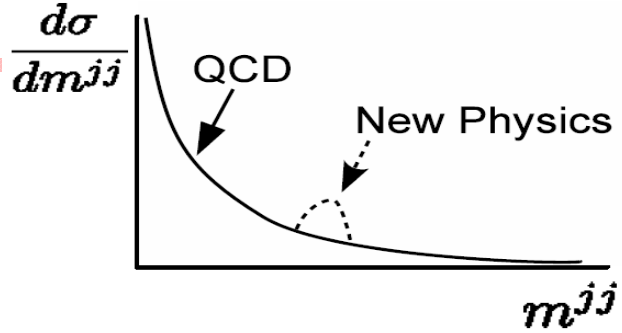
Cross Section **17 / nb** **Data / Theory**

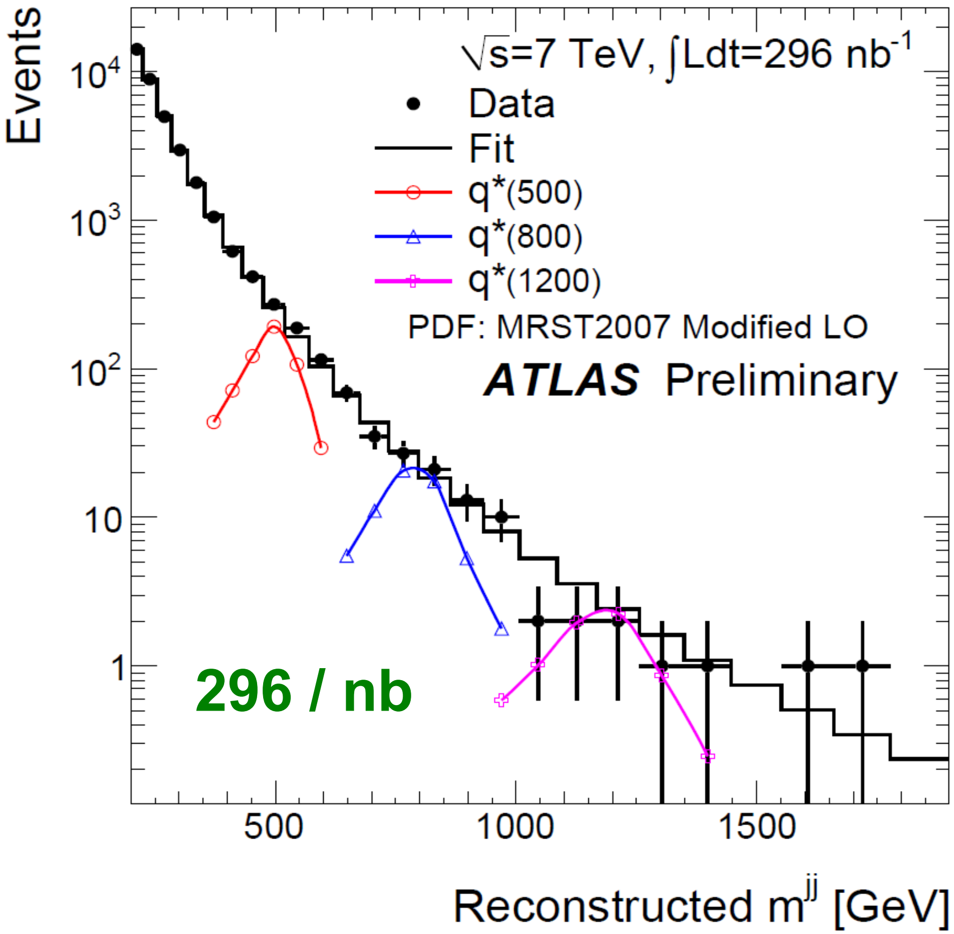


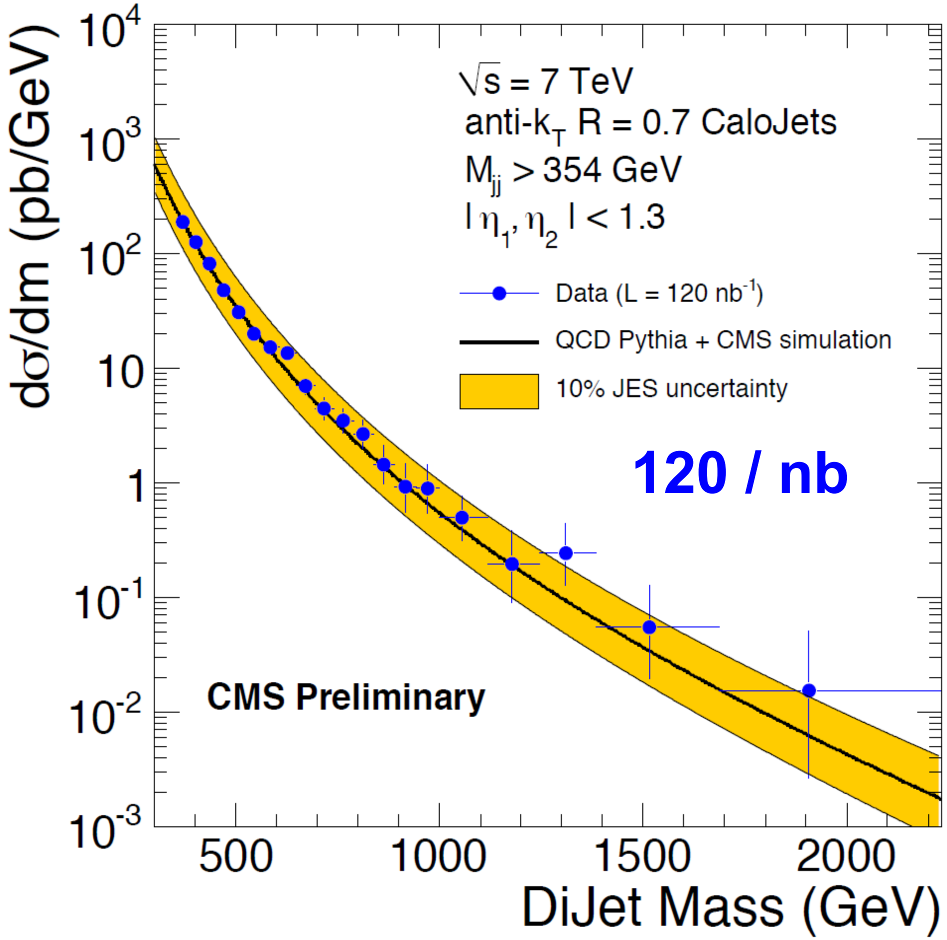


Dijet Mass Bump Hunt

No bumps **found so far!**



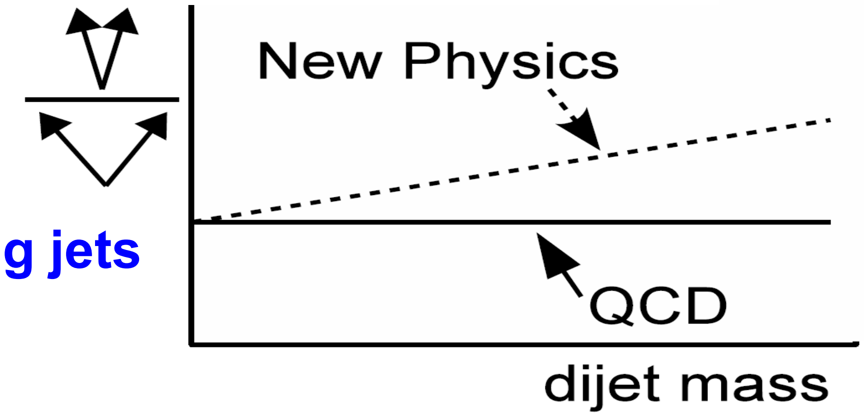




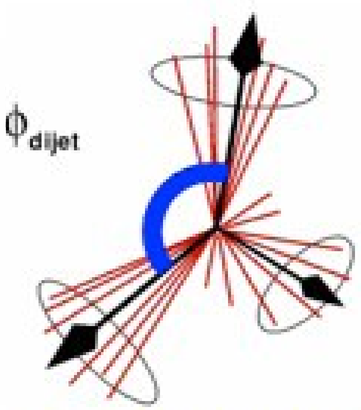
Reduction of Uncertainties 1

- **Measurements so far: Absolute jet cross sections**
  - **Inclusive jet pT or dijet mass cross sections:**
    - **Most complicated, require all uncertainties to be under control!**
- **Reduction strategy 1: Jet cross section ratios**
  - **Dijet mass cross section ratios in rapidity → new physics ?**
  - **3-jet to 2-jet cross section ratio → strong coupling α_s**
    - **Many uncertainties cancelled (luminosity, …) or reduced (JES, ...)**

$$\eta\text{-ratio} = \frac{N(|\eta_{1,2}|<0.5)}{N(0.5<|\eta_{1,2}|<1)}$$



Both leading jets in specific η region



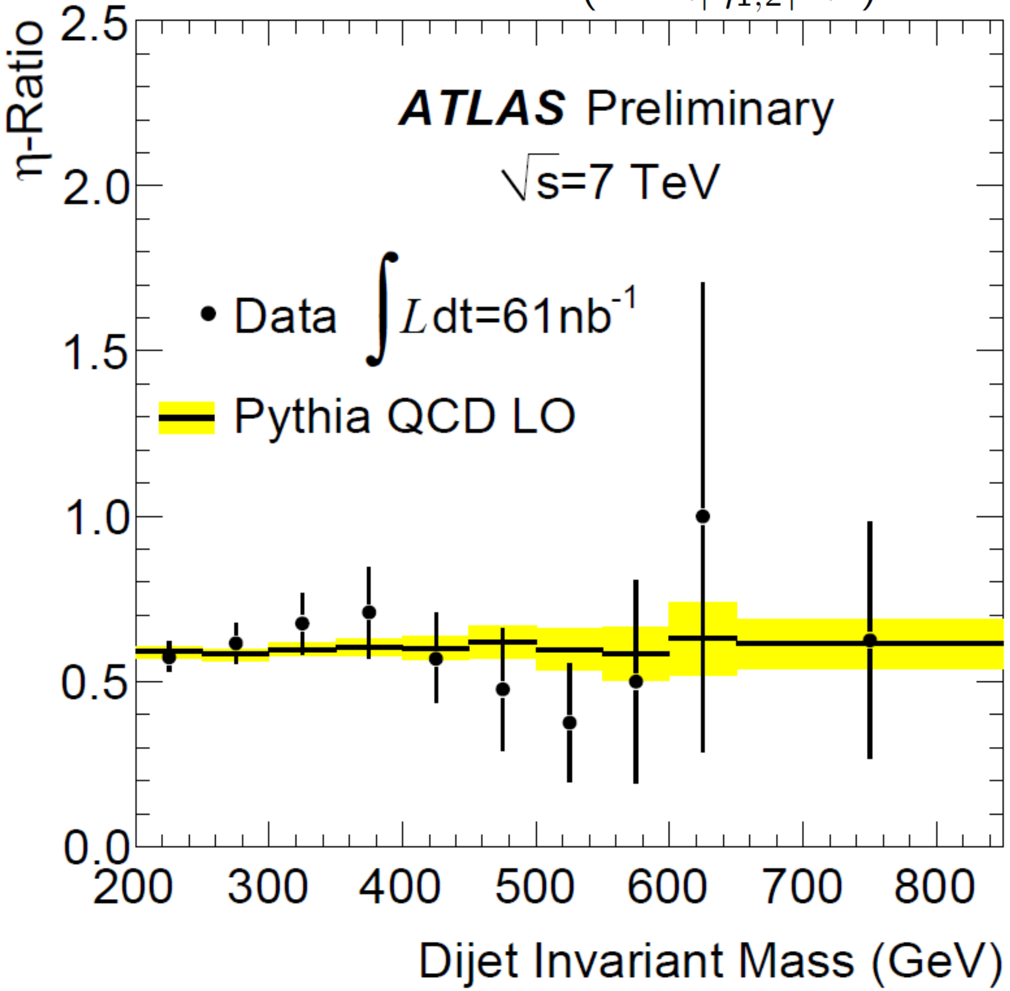
~ strong coupling α_s

jet 3

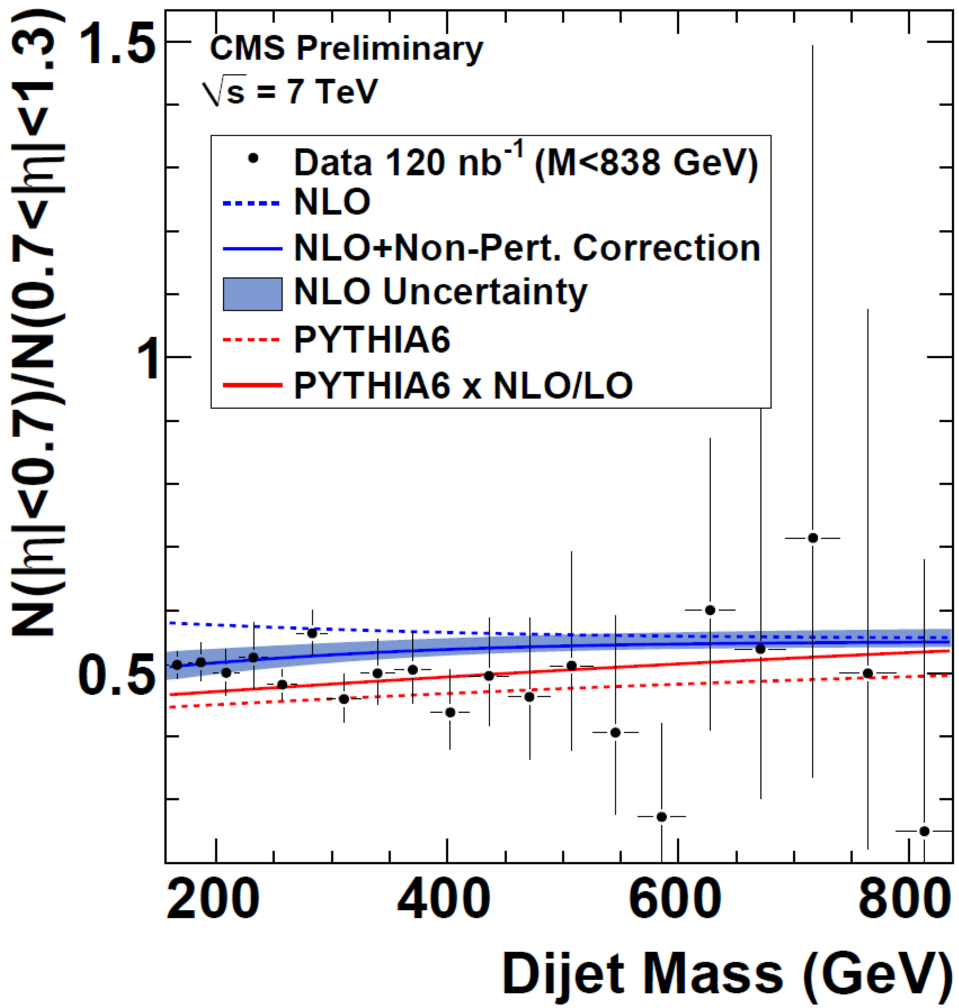
Dijet Centrality Ratio

No deviations from QCD observed!

$$\eta\text{-ratio} = \frac{N(|\eta_{1,2}|<0.5)}{N(0.5<|\eta_{1,2}|<1)}$$

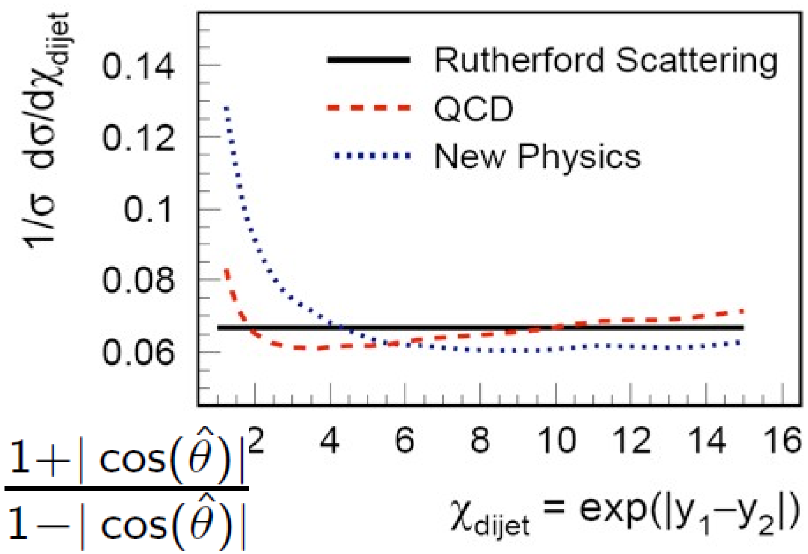


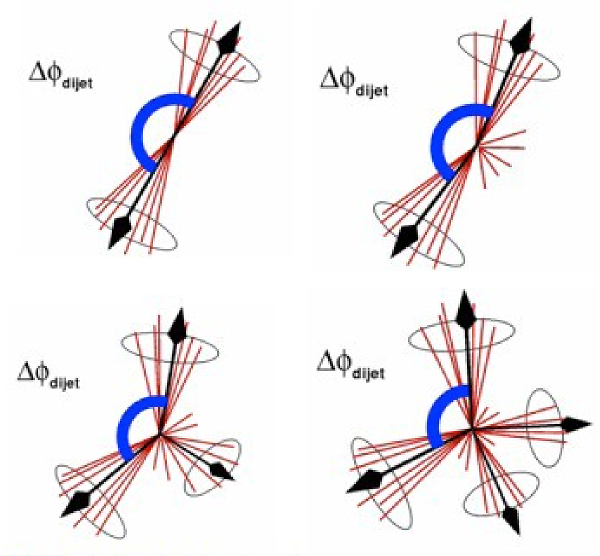
$$R = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}$$



Reduction of Uncertainties 2

- **Reduction strategy 2: Jet angular measurements**
  - Dijet chi distribution ⟶ new physics ?
  - Dijet azimuthal decorrelation ⟶ deviations from QCD radiation ?
    - Reduced sensitivity to jet energy scale (JES) or resolution (JER)
- **In addition: Normalized distributions**
  - Event shapes ⟶ Test of QCD, MC tuning
    - Less sensitive to JES, not dependent on luminosity



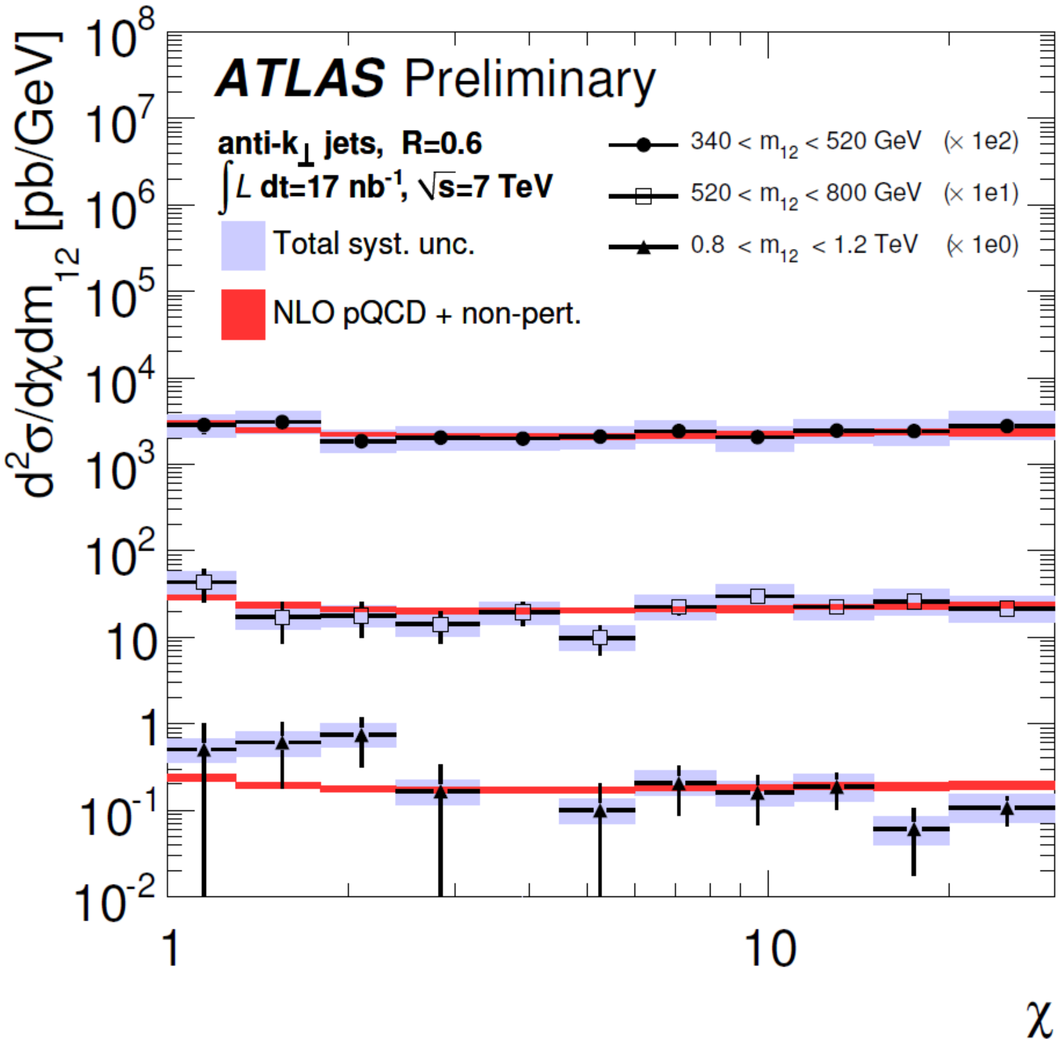


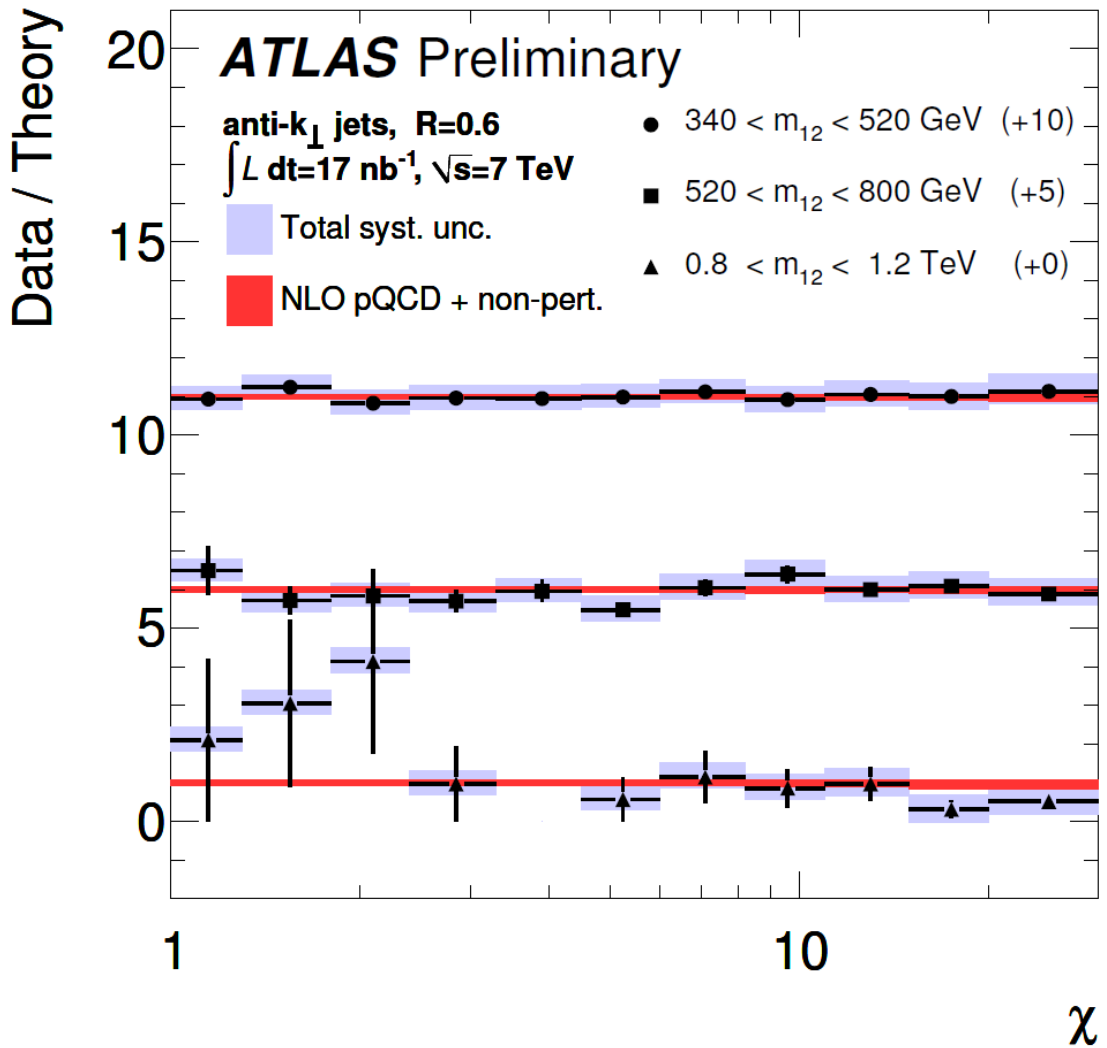
$$\chi = \exp(|\eta_1 - \eta_2|) = \frac{1 + |\cos(\hat{\theta})|}{1 - |\cos(\hat{\theta})|}$$

Dijet Chi 1

Int. Luminosity 17 / nb

Compatible with QCD!



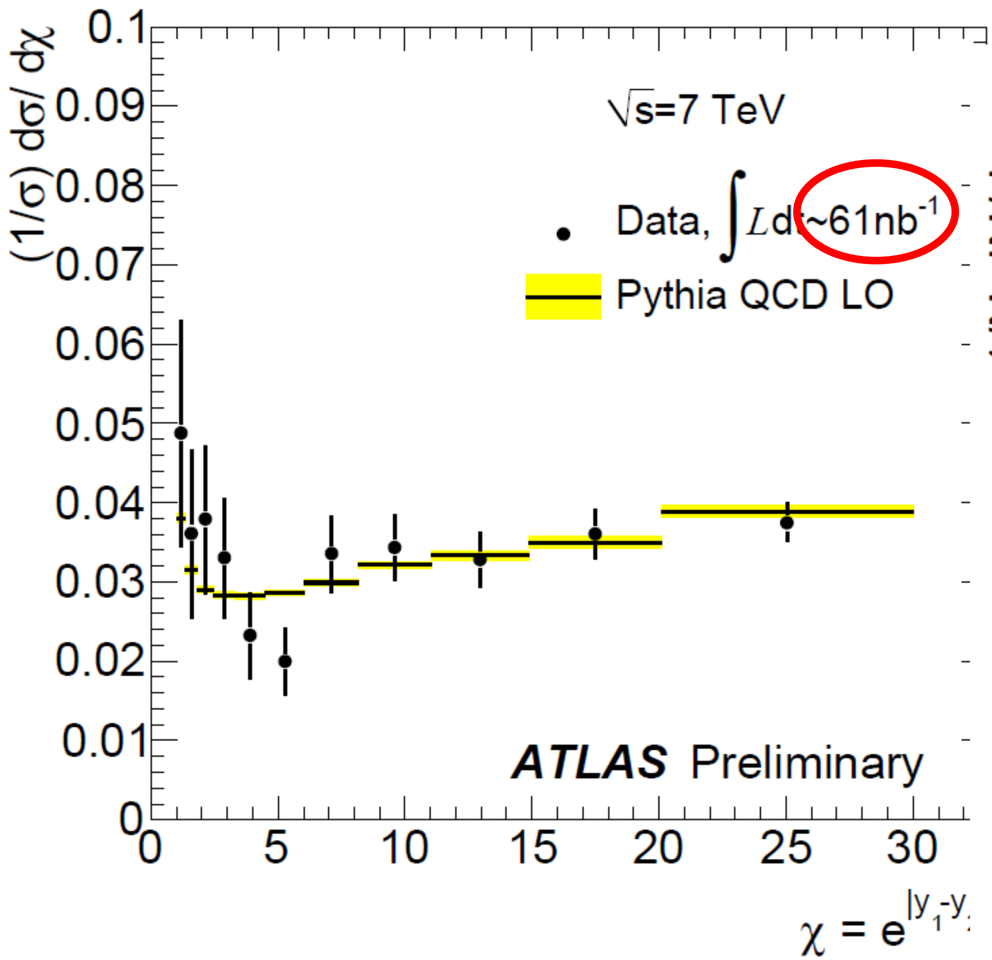


Dijet Chi 2

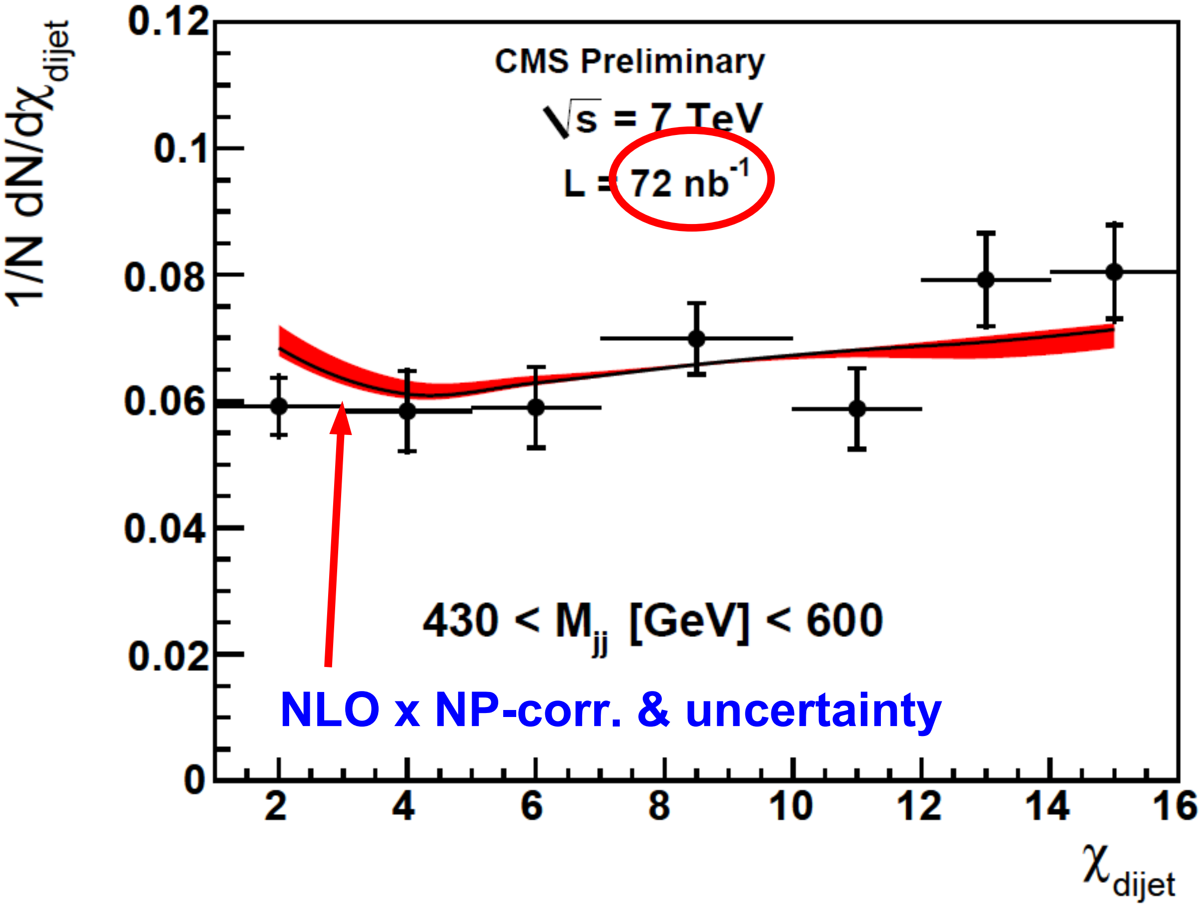
> threefold increase in int. Lumi

Still no deviations from QCD observed!

520 < M_{jj} / GeV < 680

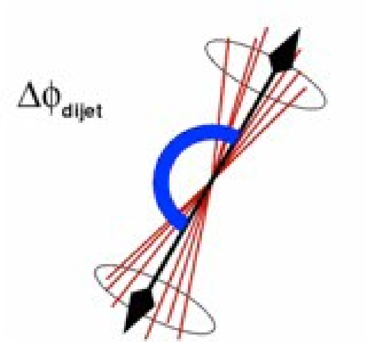


430 < M_{jj} / GeV < 600

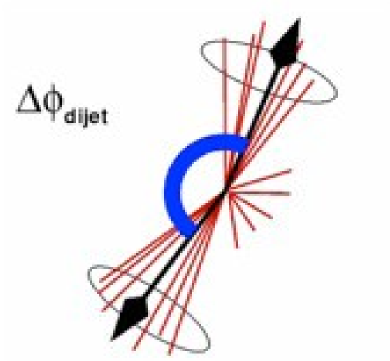


Dijet Azimuthal Decorrelation

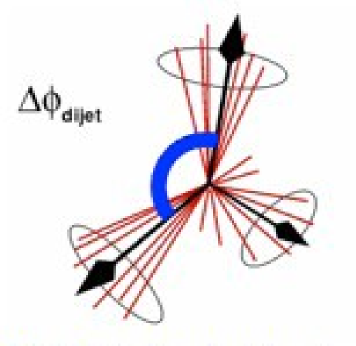
Dijets in pp collisions:



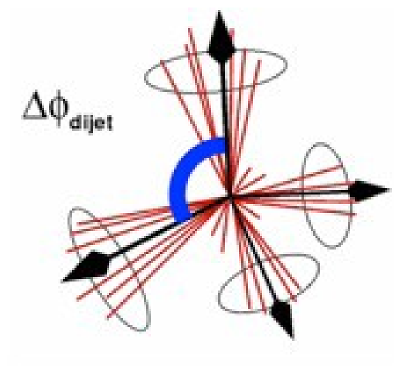
$\Delta\varphi$ dijet = π →
Exactly two jets, no further radiation



$\Delta\varphi$ dijet small deviations from π →
Additional soft radiation outside the jets



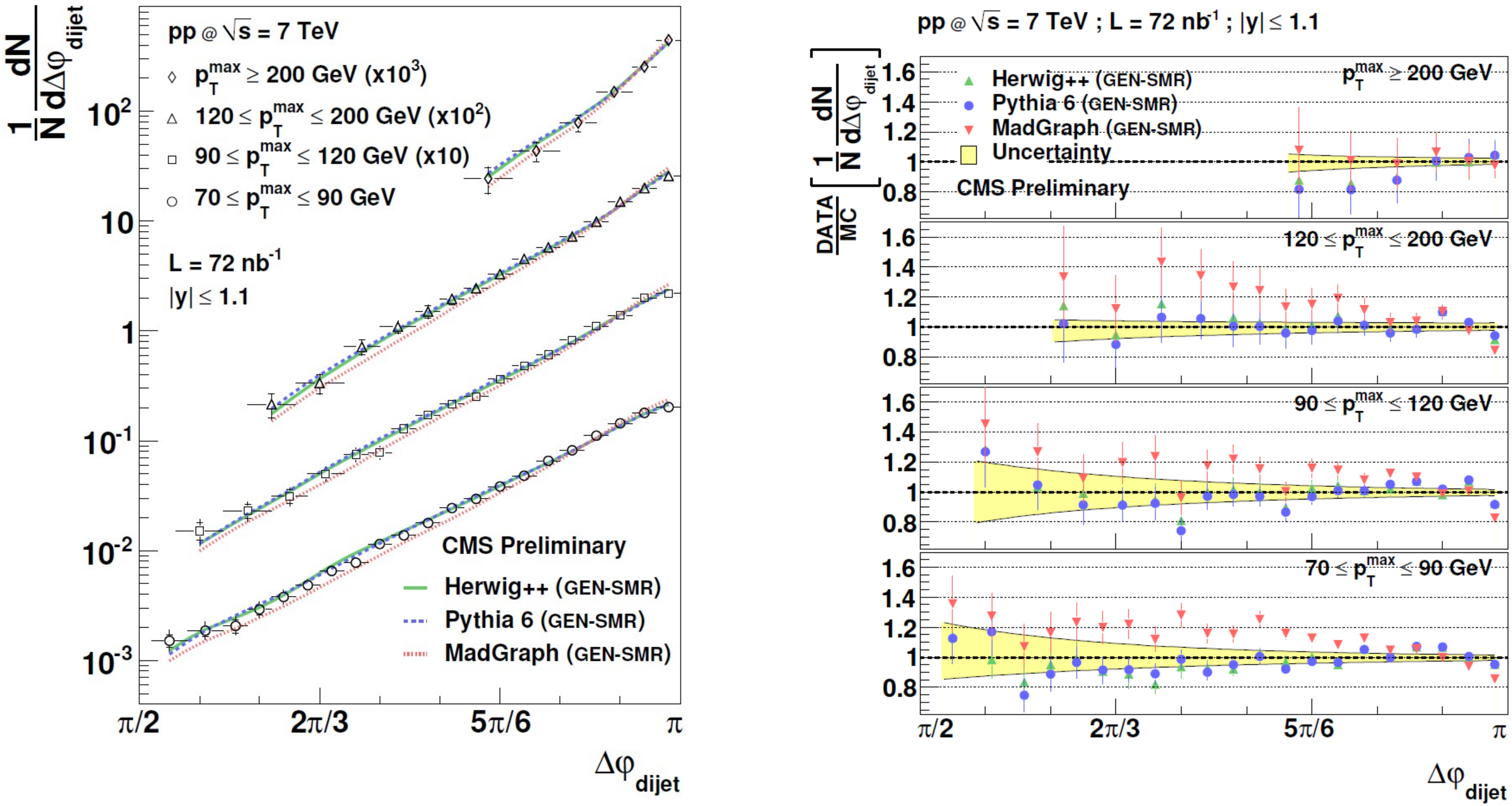
$\Delta\varphi$ dijet as small as $2\pi/3$ →
One additional high-pT jet



$\Delta\varphi$ dijet small – no limit →
Multiple additional hard jets in the event

Dijet Azimuthal Decorrelation

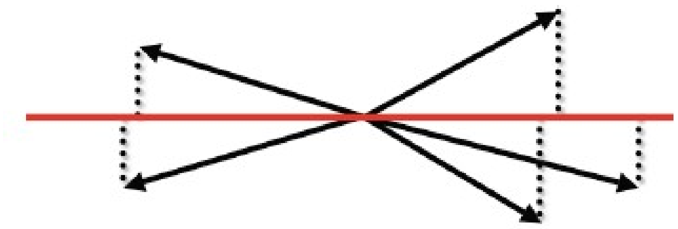
Data well described by Pythia or Herwig++, less so by MadGraph



Event Shapes

Definition:

Transverse global Thrust



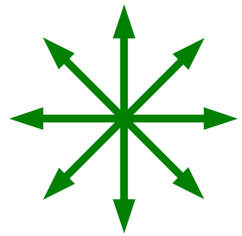
Similar as Event Shapes in e^+e^- and ep

- **In praxis, need to restrict rapidity range: |η| < 1.3 → Transverse central thrust**
- **Less sensitive to JES & JER uncertainty**
- **No luminosity uncertainty**
- **Useful for MC tuning**

$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

linear ~ dijet

T → 0



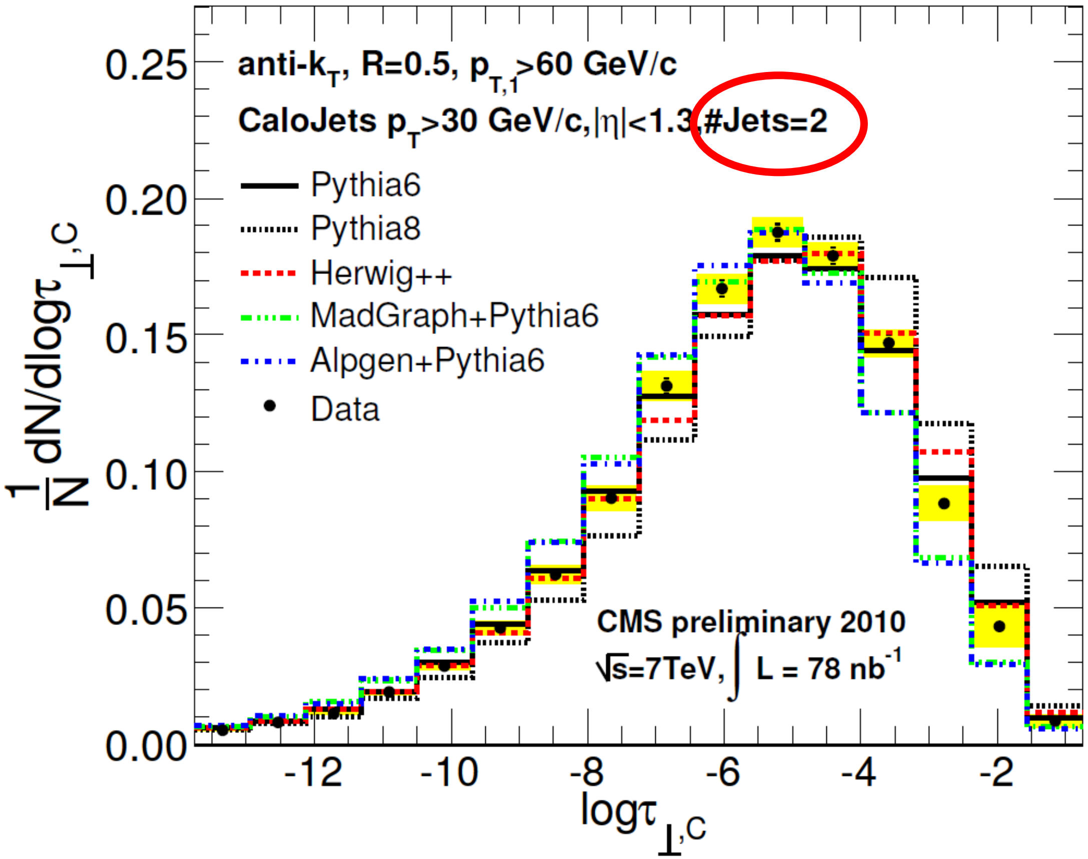
spherical ~ multijet

T → 2/π

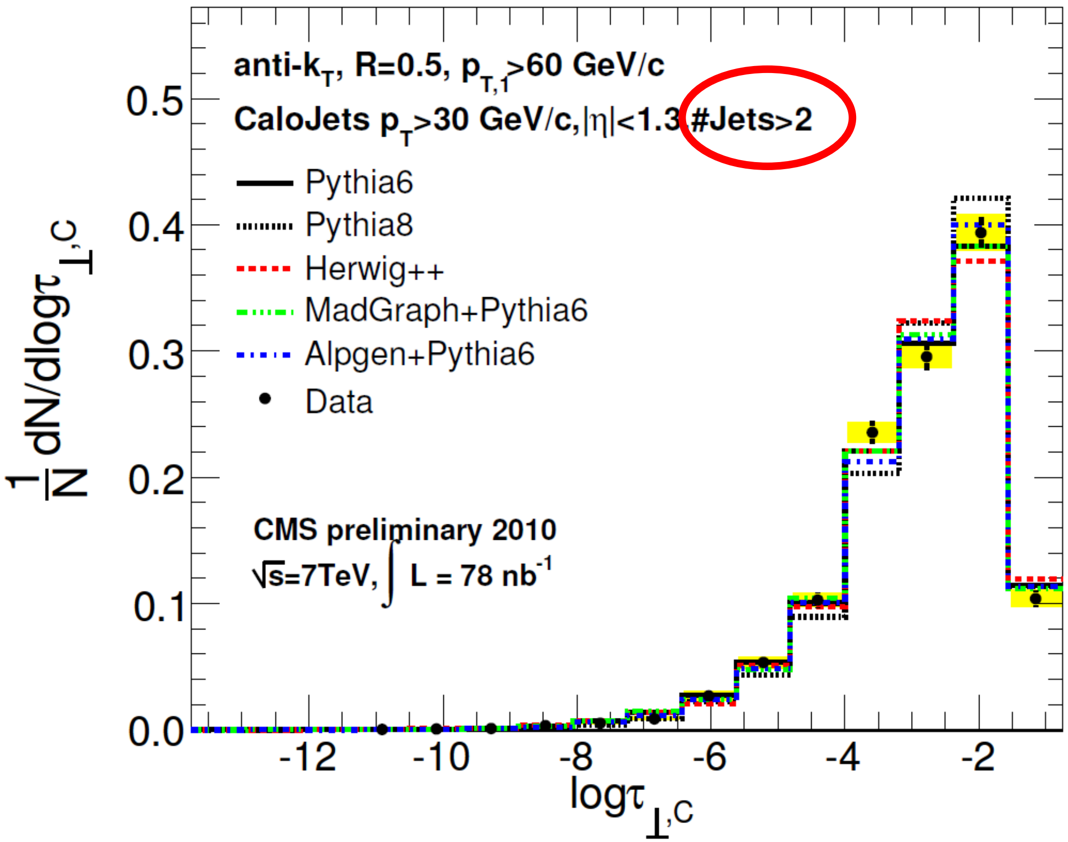
Redefine to get $\tau_{\perp,g} \equiv 1 - T_{\perp,g}$ → 0 in LO dijet case

Event Shapes

- **Dijet case:**
  - **Good description by Pythia6, Herwig++**
  - **Alpgen & MadGraph off as well as Pythia8**

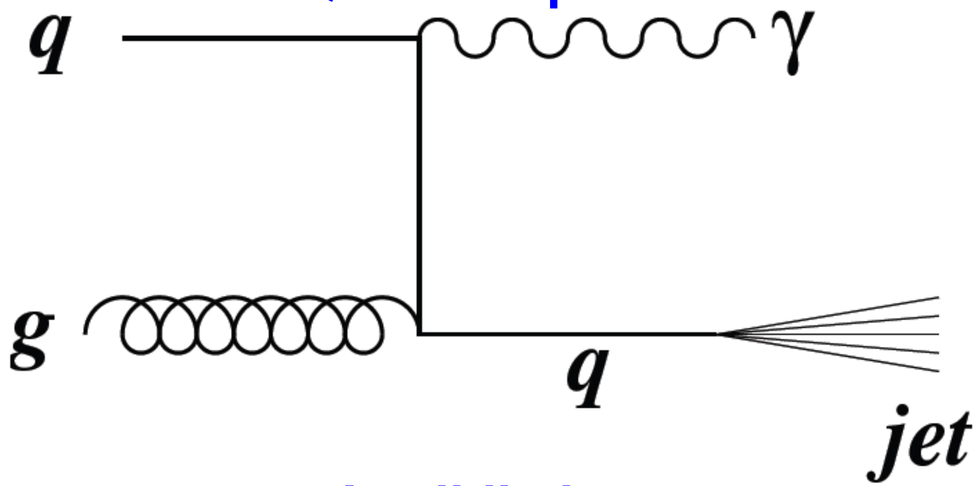


- **Multijet case:**
  - **Pythia6, Herwig++ still ok**
  - **Alpgen & MadGraph better**

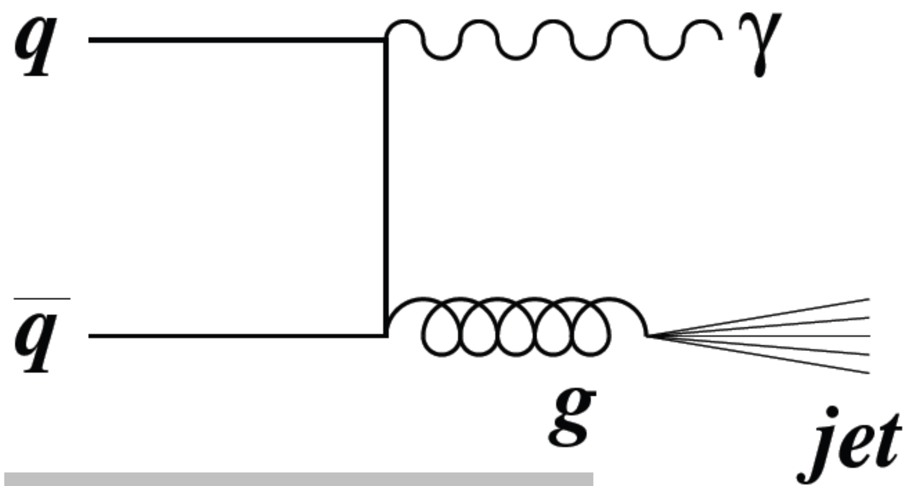


First Light

QCD Compton



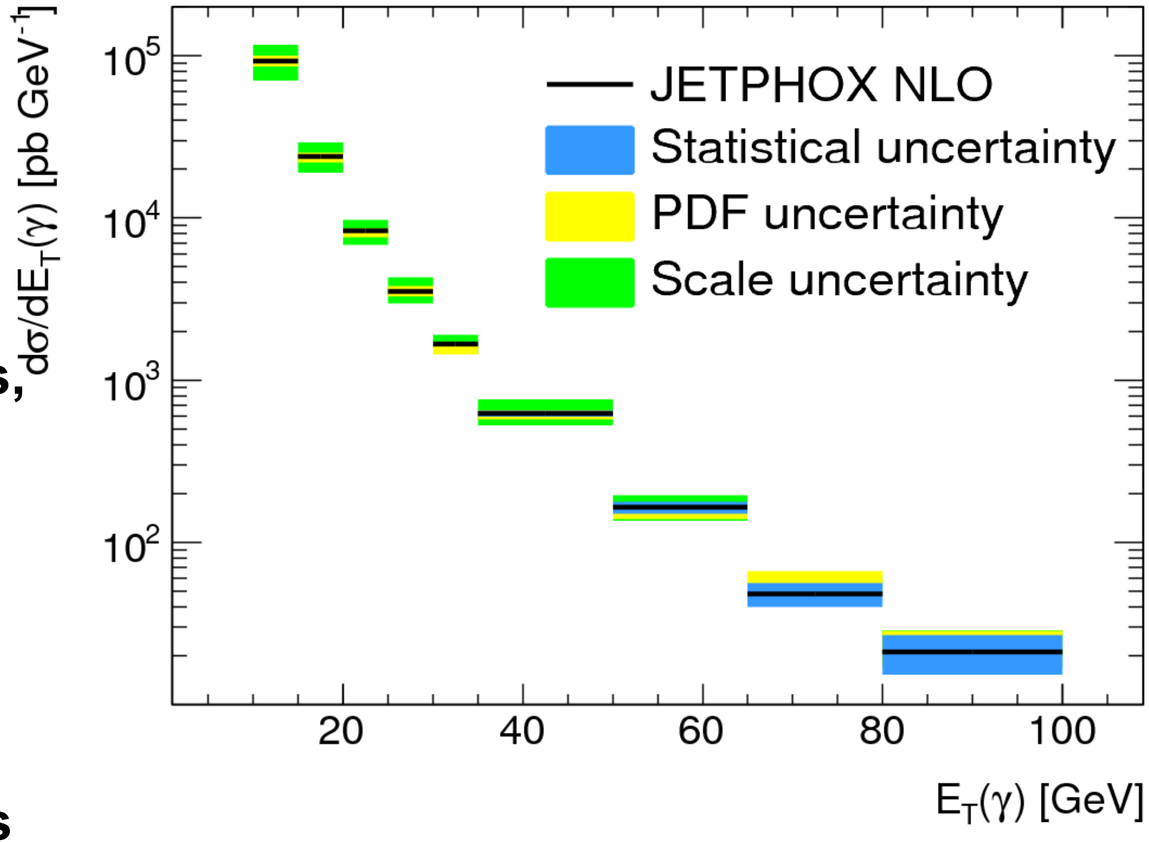
Annihilation



See lectures from Jeff Owens

Expectations

- **Prompt photon measurements provide:**
  - **Test of QCD**
  - **Another handle on gluon PDF**
  - **Background knowledge for Higgs, SUSY, etc. searches**

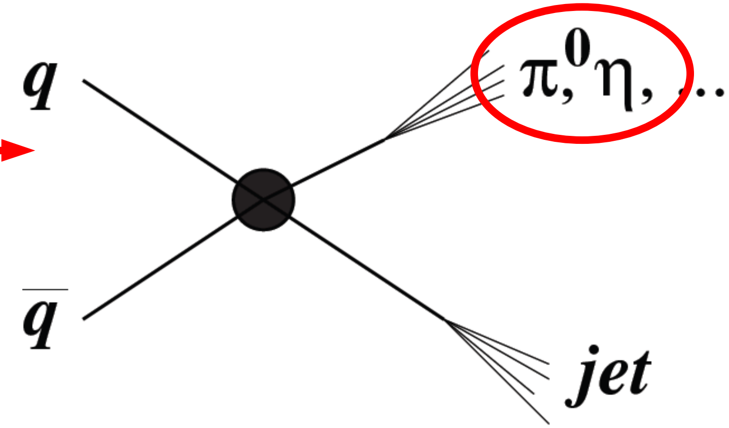


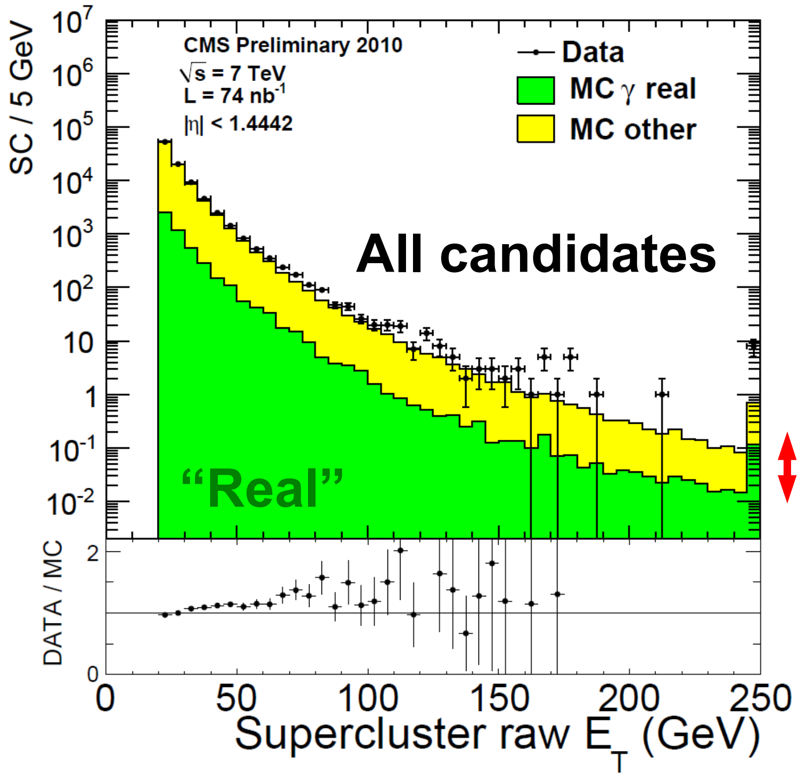
- **What counts as prompt photon?**
  - **Direct photons, previous slide**
  - **NLO: Photons radiated off quarks (fragmentation photon) ?**
  - **Need to define isolation criterion!**

Settings: E_T > 10 GeV
Isolation: E_T(parton, ΔR < 0.4) < 5 GeV
ATLAS ECAL: $|\eta|$ < 1.37; 1.52 < $|\eta|$ < 2.37

Photon Difficulties

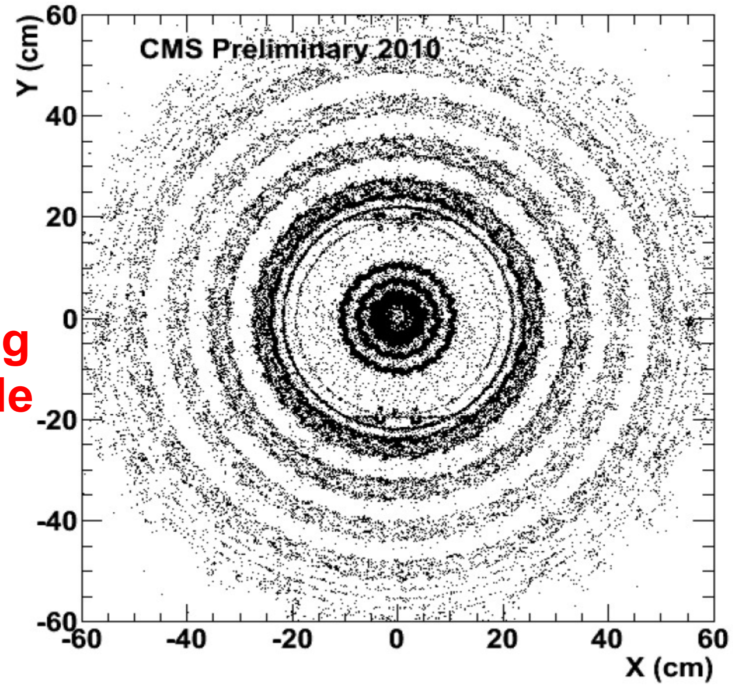
- Isolation definition
- Background from decays, in particular π^0, η
- Background from jets faking a photon
- Photon conversions in detector material





Fake photons dominating by > 1 order of magnitude
(After preselection only, background scaled to match yield)

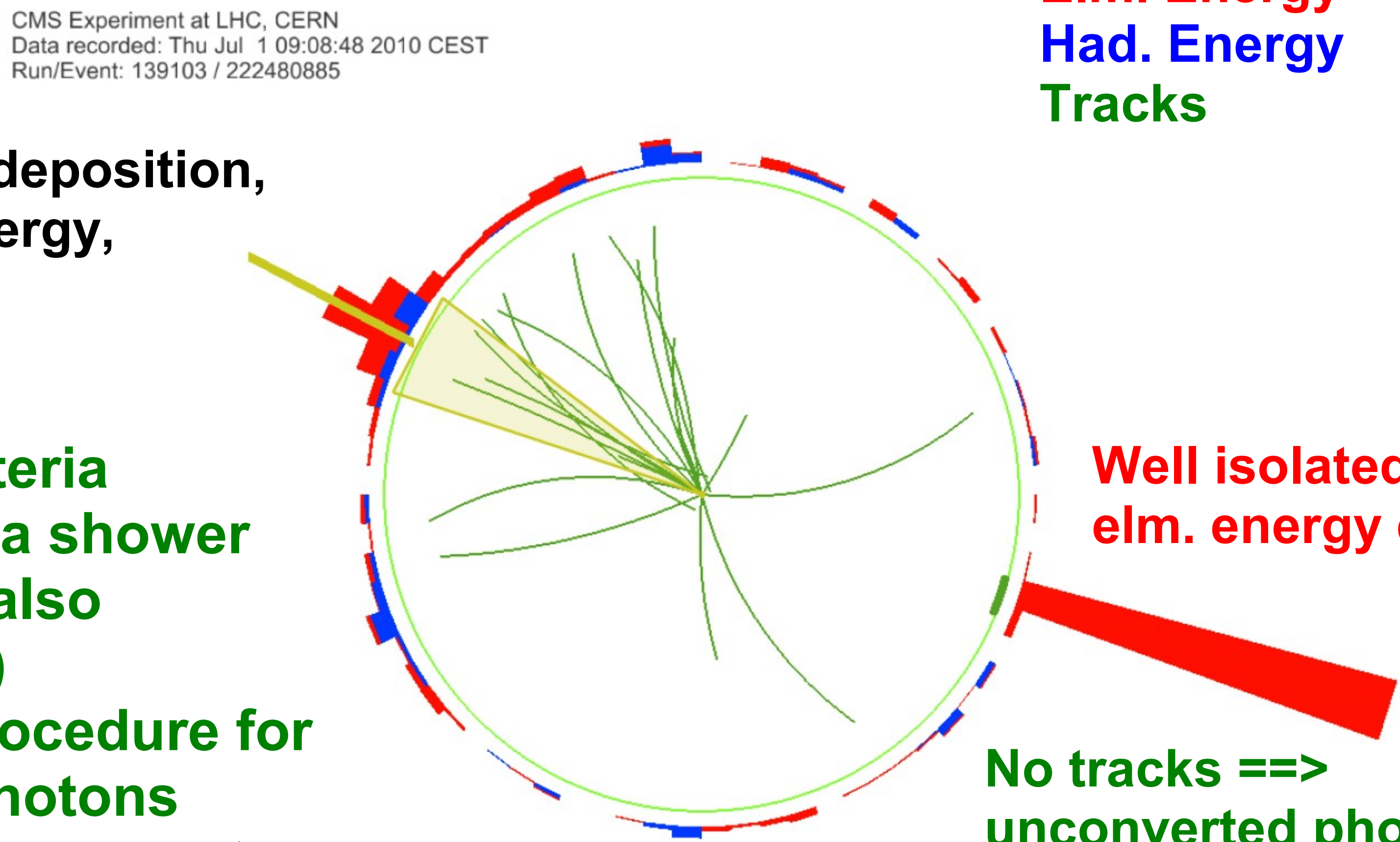
X ray of CMS Pixel



Refined Photon ID

Well balanced photon + jet event

Typical jet:
Broad energy deposition,
elm. & had. energy,
tracks



Elm. Energy
Had. Energy
Tracks

Apply
- Isolation criteria
- Photon ID via shower shape (η, φ also longitudinal)
- Recovery procedure for converted photons

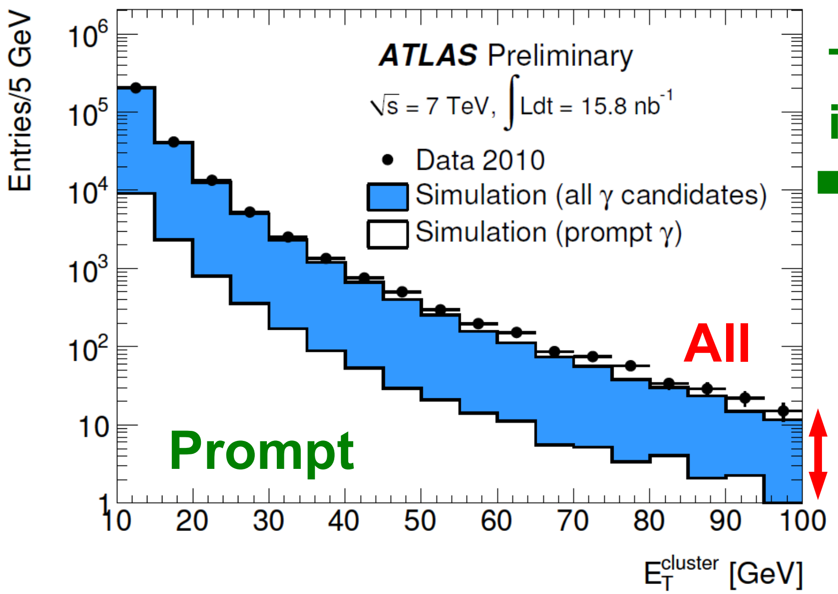
to refine measurement

Well isolated, narrow elm. energy cluster

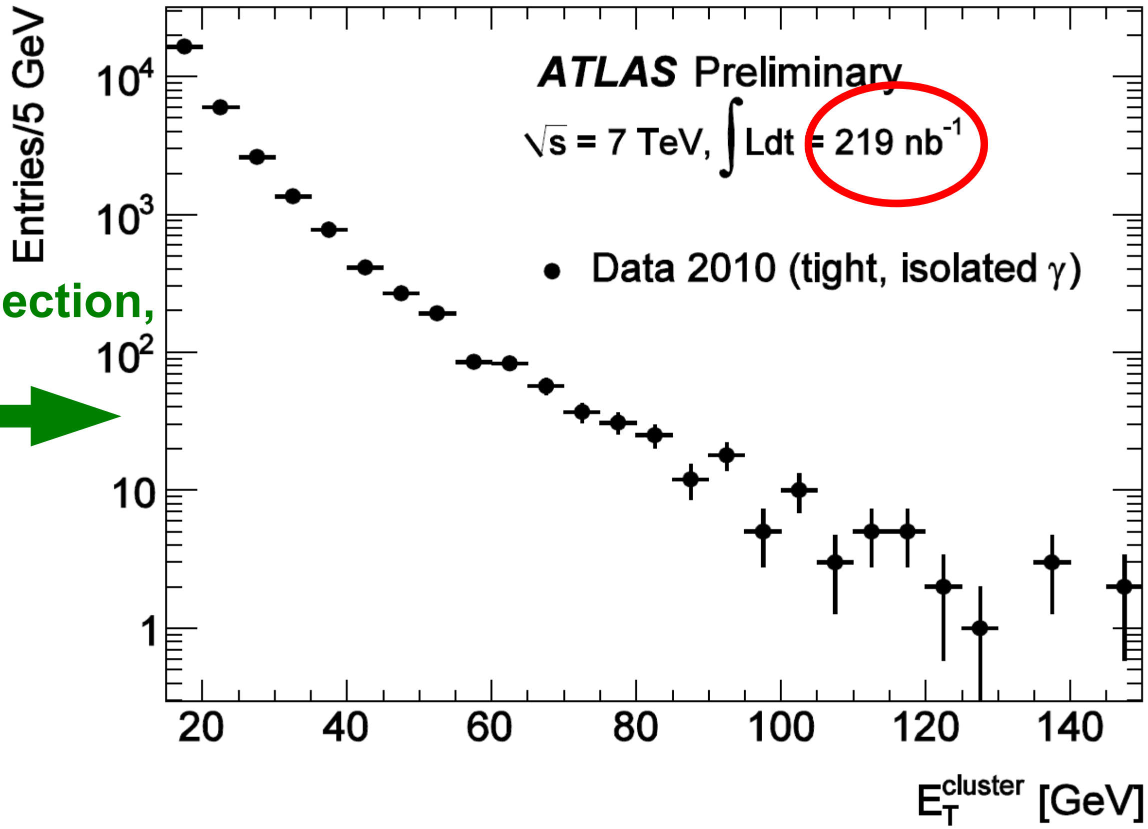
No tracks ==> unconverted photon
(Otherwise try to find conversion vertex)

Prompt Photon Yield

- **Strategies for isolation and photon ID in ATLAS and CMS similar but different in the details. Recall:**
  - **ATLAS: Liquid Argon sampling calorimeter**
  - **CMS: Crystal elm. and brass/scintillating fibre had. calorimeter**
- **Work on cross sections in progress ...**



Tight selection, isolation



Standard Candles

W/Z Measurements

Signal Background

$$\sigma = \frac{N - B}{\mathscr{L}\, A\, \varepsilon}$$

Luminosity Efficiency

Acceptance

- **Uncertainties:**
  - **ΔN: Purely statistics; improves with integrated luminosity**
  - **ΔB, ΔA, Δε: Exp. & theor.; improves over time with better understanding**
    - **Background, acceptance & efficiency estimations, i.a. using MC detector simulations**
  - **ΔL: Luminosity uncertainty; improves with better understanding of LHC beam parameters and luminosity monitors**

Typical W/Z Event Selections

Differences in details between ATLAS and CMS depending on detector coverage, fiducial volumes and performance

Electron channels:

$W \to e\nu$: $E_{T,e} > 20 - 30$ GeV
$|\eta_e| < 2.4 - 2.5$
MET > 25 – 30 GeV
$M_T > 40$ GeV
Veto 2nd e from Z

$Z \to ee$: $E_{T,e} > 15 - 20$ GeV
$|\eta_e| < 2.4 - 2.5$
$60 - 70 < M_{ee} < 110 - 120$ GeV

Muon channels:

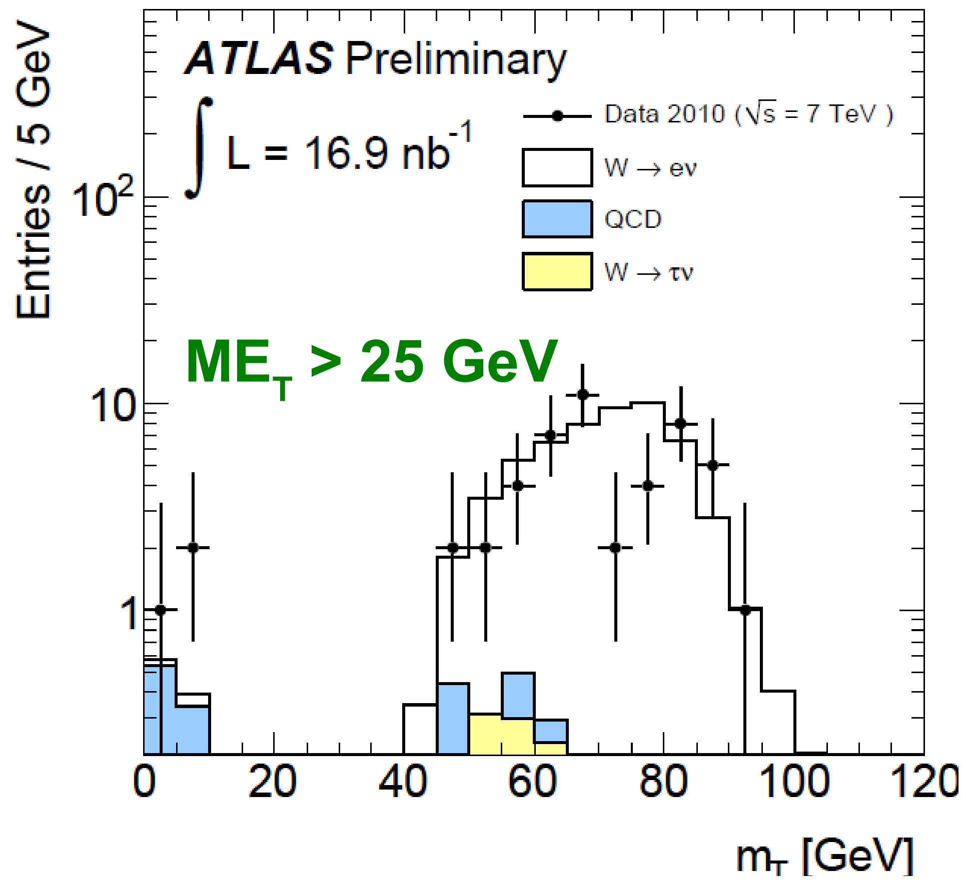
$W \to \mu\nu$: $p_{T,\mu} > 20$ GeV
$|\eta_\mu| < 2.0 - 2.5$
MET > 25 – 30 GeV
$M_T > 40$ GeV
Veto 2nd μ from Z

$Z \to \mu\mu$: $p_{T,\mu} > 15 - 20$ GeV
$|\eta_\mu| < 2.0 - 2.5$
$60 - 70 < M_{\mu\mu} < 110 - 120$ GeV

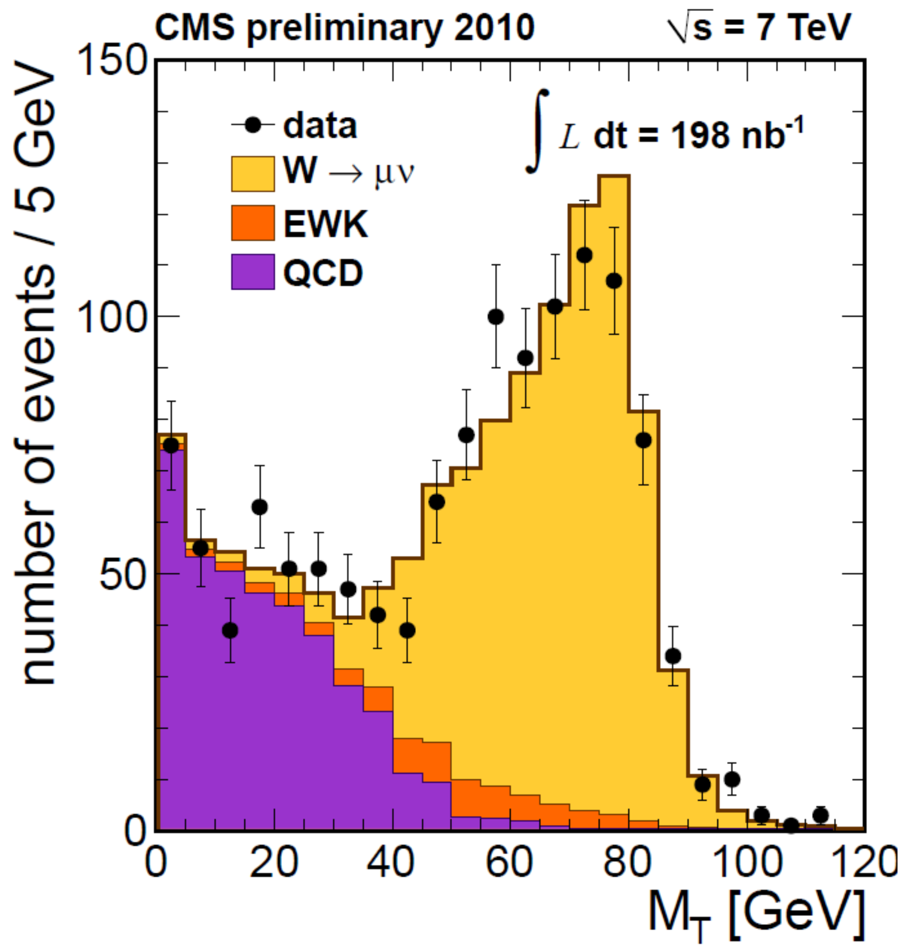
Lepton isolation: Radii in (η,Φ) of 0.3 to 0.5 are imposed
Lepton ID: Criteria might be looser for μ compared to e and for Z→ll compared to W→lν
Lepton Pairs: Opposite charges required

W Transverse Mass Distributions

ATLAS: W → eν



CMS: W → μν

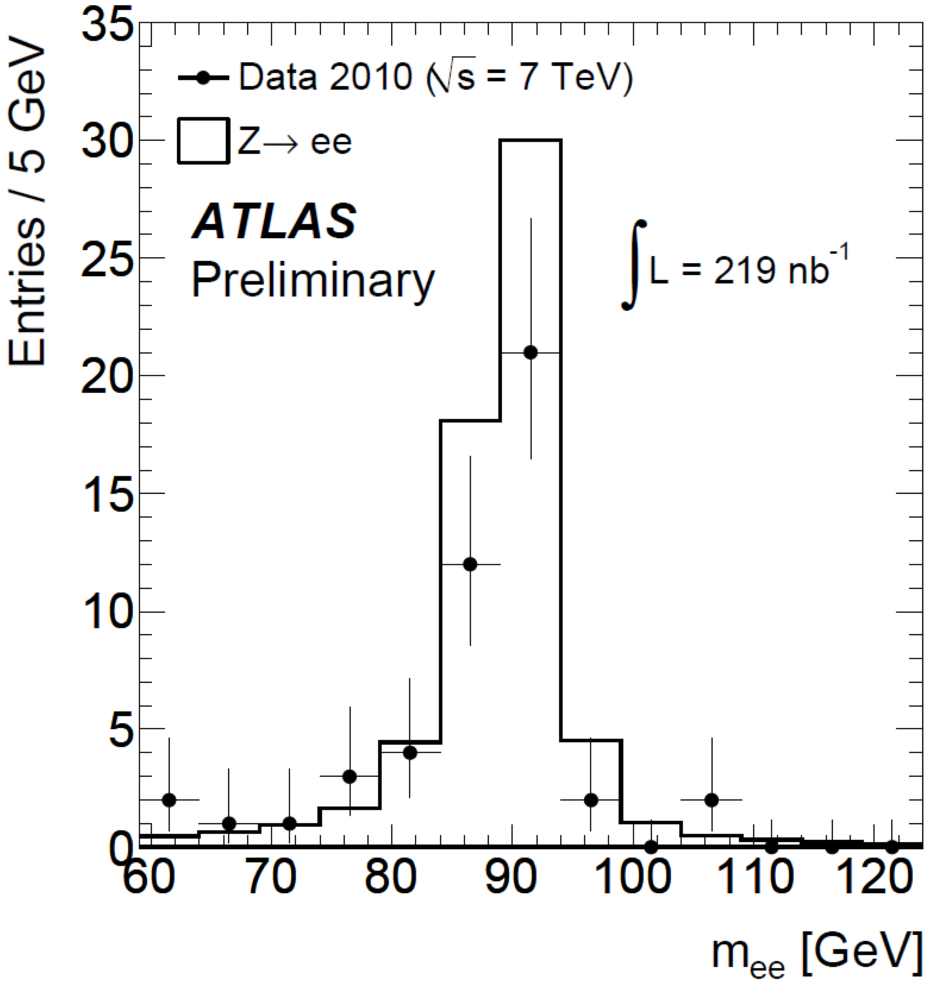


$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

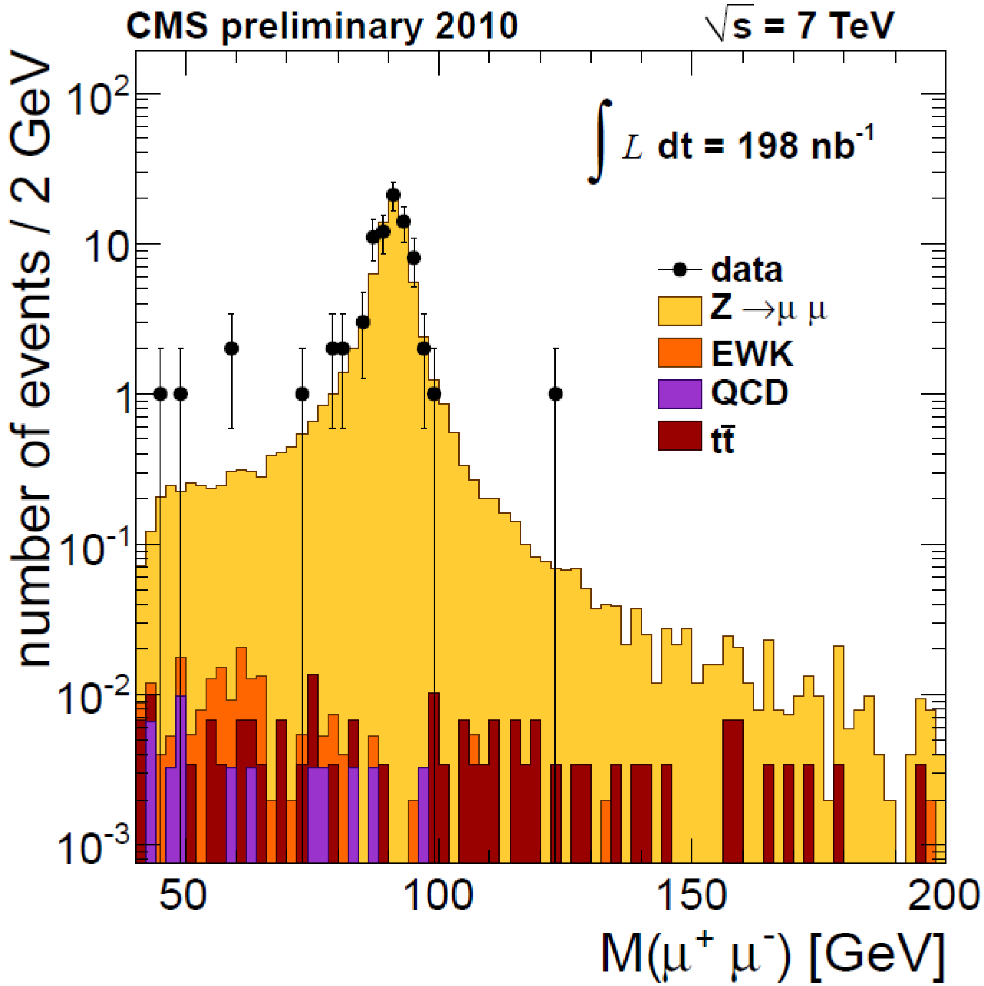
Using missing E_T instead of neutrino

Z Mass Distributions

ATLAS: Z → ee



CMS: Z → μμ



Inclusive W/Z Production

CMS Cross Sections,
L_{int} = 198 / nb

6.15 ± 0.29 nb **NNLO FEWZ** **W: ~8-9% Precision**

$$\sigma(pp \to W^+ + X \to \mu^+\nu + X) = 5.75 \pm 0.26(\text{stat.}) \pm 0.36(\text{syst.}) \pm 0.63(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to W^+ + X \to e^+\nu + X) = 5.18 \pm 0.26(\text{stat.}) \pm 0.42(\text{syst.}) \pm 0.57(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to W^+ + X \to \ell^+\nu + X) = 5.50 \pm 0.18(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.61(\text{lumi.})\ \text{nb}.$$

4.29 ± 0.23 nb **NNLO FEWZ**

$$\sigma(pp \to W^- + X \to \mu^-\overline{\nu} + X) = 3.39 \pm 0.15(\text{stat.}) \pm 0.21(\text{syst.}) \pm 0.37(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to W^- + X \to e^-\overline{\nu} + X) = 4.13 \pm 0.24(\text{stat.}) \pm 0.34(\text{syst.}) \pm 0.45(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to W^- + X \to \ell^-\overline{\nu} + X) = 3.60 \pm 0.13(\text{stat.}) \pm 0.19(\text{syst.}) \pm 0.40(\text{lumi.})\ \text{nb}.$$

0.97 ± 0.04 nb **NNLO FEWZ** **Z: ~12% Precision**

$$\sigma(pp \to Z(\gamma^*) + X \to \mu^+\mu^- + X) = 0.881^{+0.104}_{-0.097}(\text{stat.})^{+0.042}_{-0.034}(\text{syst.}) \pm 0.097(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to Z(\gamma^*) + X \to e^+e^- + X) = 0.884^{+0.118}_{-0.108}(\text{stat.})^{+0.076}_{-0.059}(\text{syst.}) \pm 0.097(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to Z(\gamma^*) + X \to \ell^+\ell^- + X) = 0.882^{+0.077}_{-0.073}(\text{stat.})^{+0.042}_{-0.036}(\text{syst.}) \pm 0.097(\text{lumi.})\ \text{nb}.$$

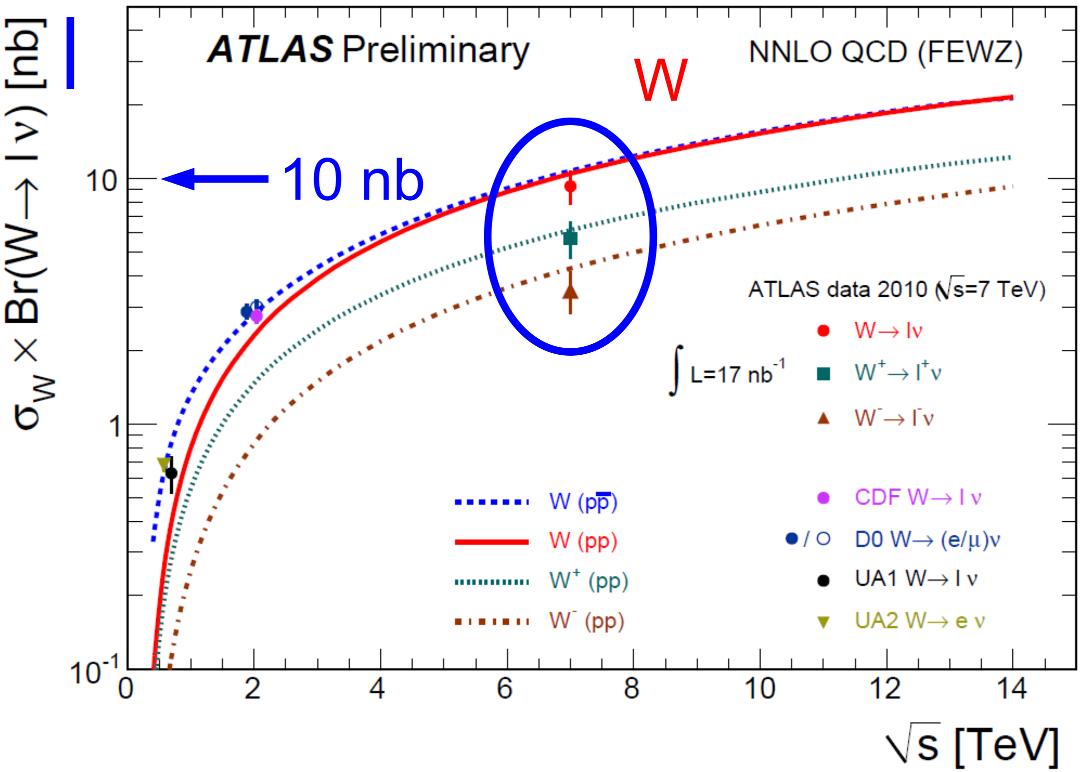
Theory (PDF, scale): 4-5% **Lumi: 11%**

ATLAS Z combined,
L_{int} = 225 / nb

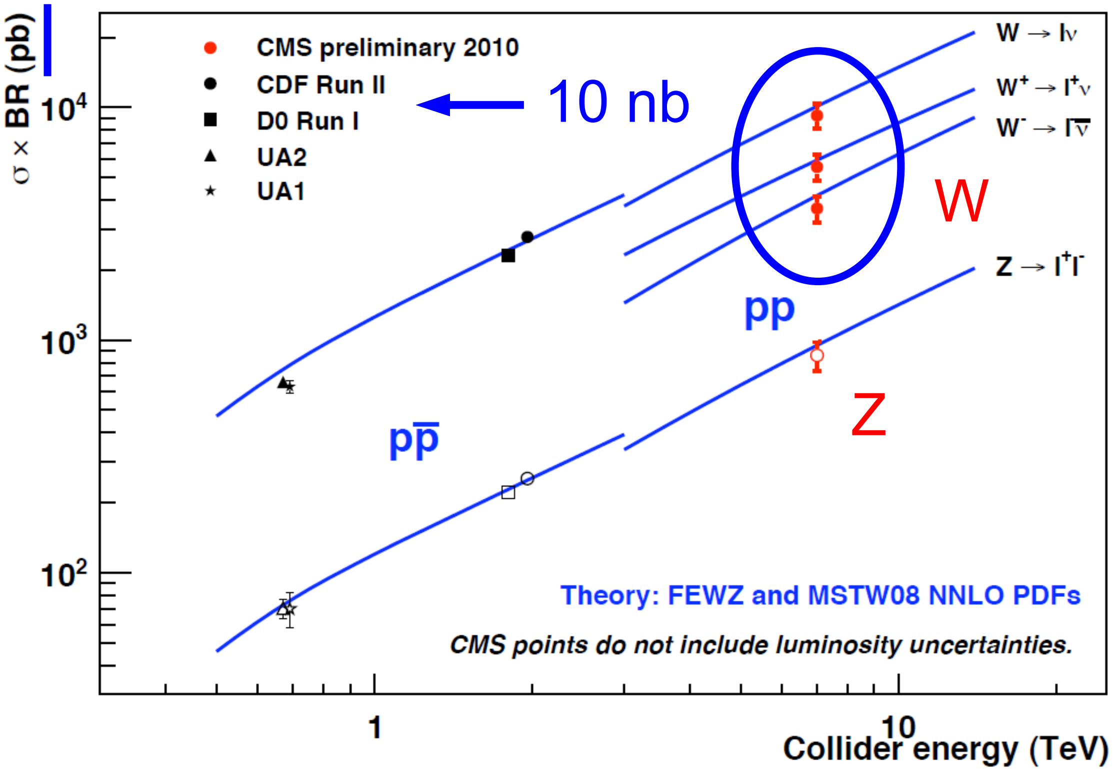
$$[0.83 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \pm 0.09(\text{lumi})]\ \text{nb}$$

Very good agreement, need more data!

Inclusive W/Z Production



CMS:
W+, W- and W, Z production, e, μ combined

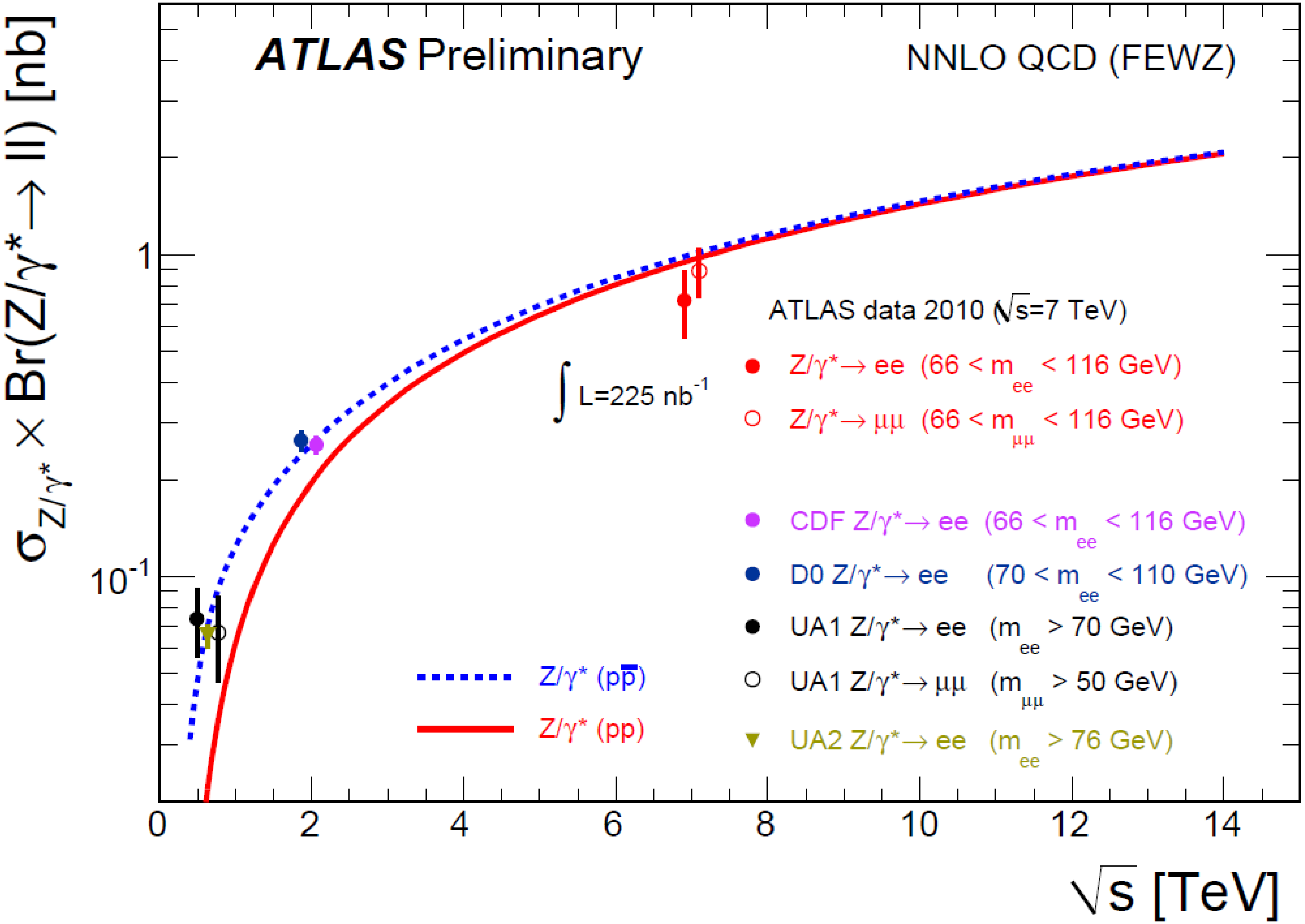


ATLAS:
W+, W- and W production, e, μ combined

Inclusive Z Production

ATLAS Z Cross Sections

Z production e, μ separate



Ratios, W plus Jets

CMS: W / Z Ratio

$$\frac{\sigma(W)}{\sigma(Z(\gamma^*))} = \frac{N_W}{N_Z}\frac{\varepsilon_Z}{\varepsilon_W}\frac{A_Z}{A_W}$$

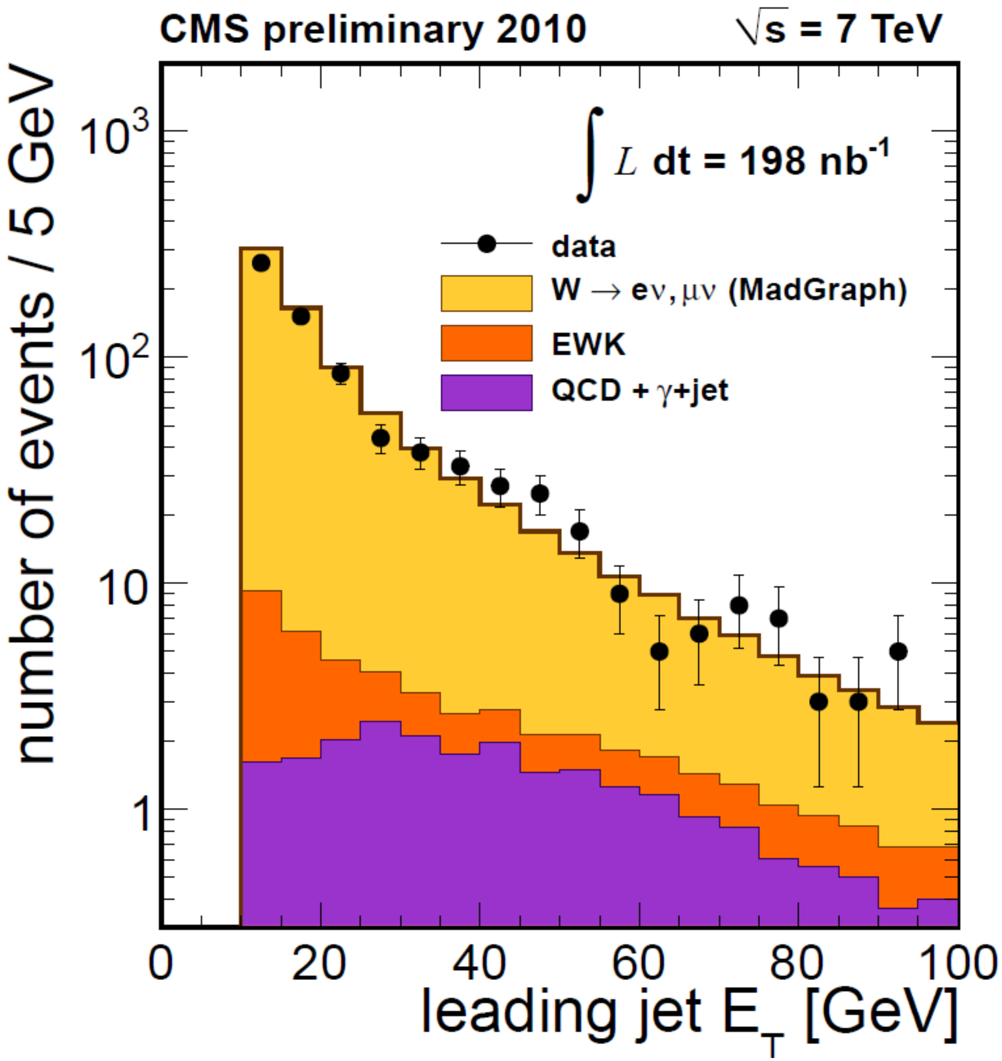
Attention:
Different efficiencies, acceptances

$$10.46^{+0.99}_{-0.88}(\text{stat.})^{+0.65}_{-0.56}(\text{syst.})$$

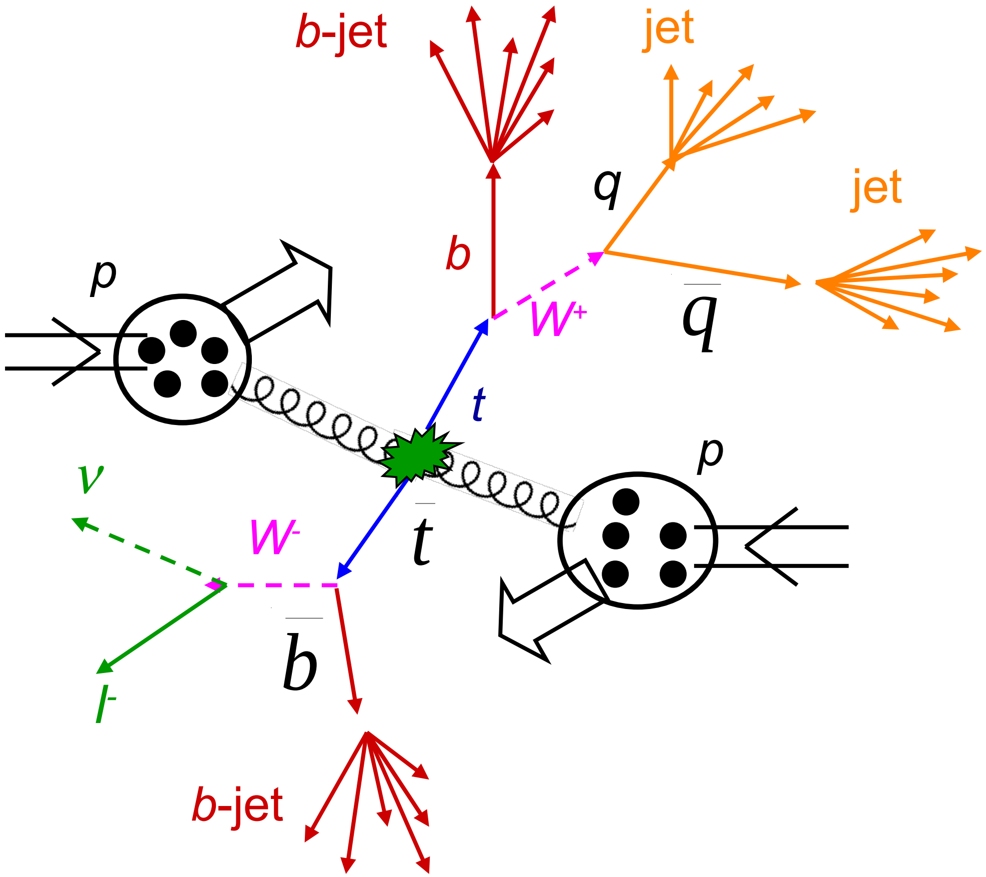
Theory: 10.74 ± 0.04

Reduced syst. exp. uncertainties also in W+ / W- or boson + N jets/ (N+1) jets ratios

W→eν, μν + Njets distribution



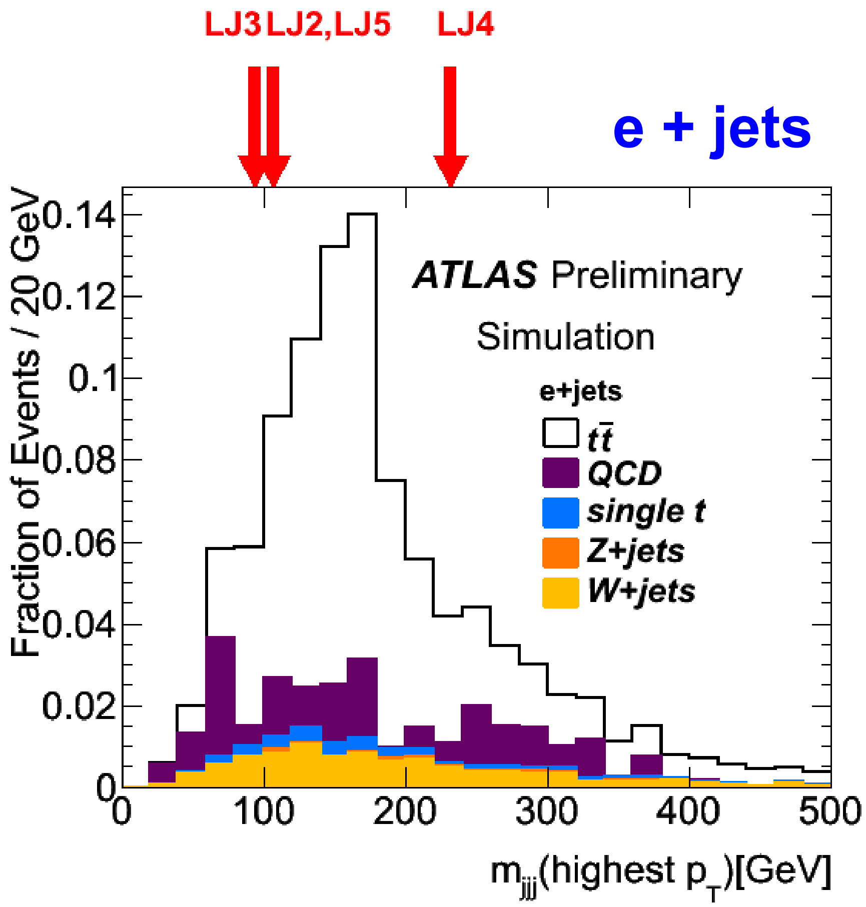
To the Top

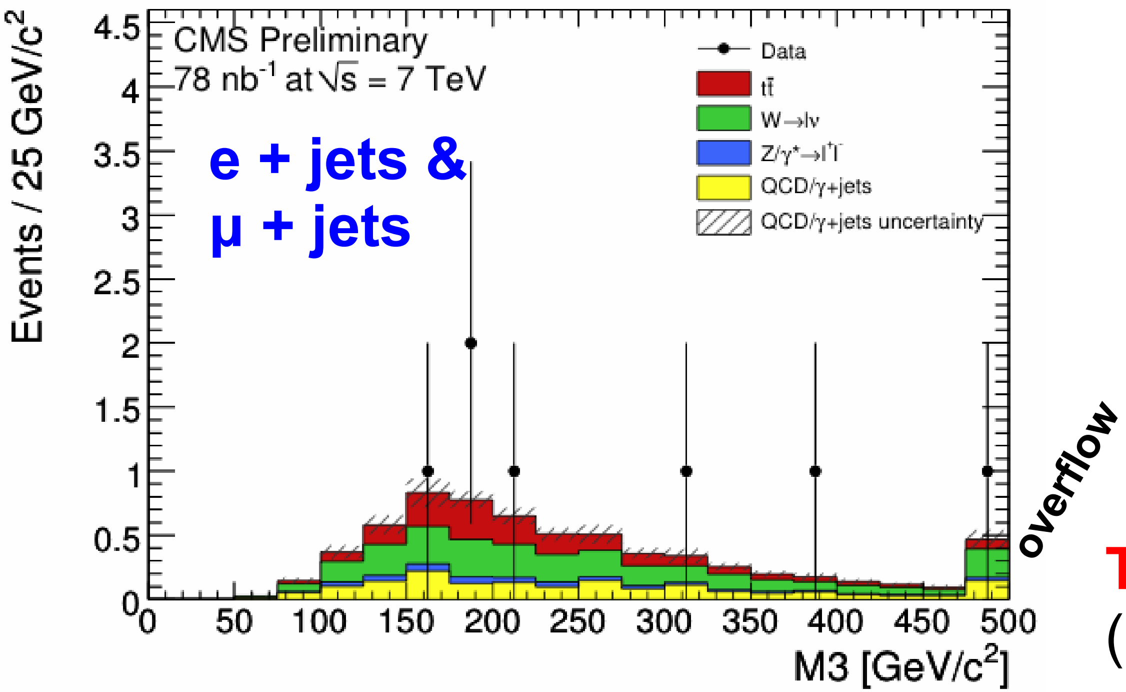


See also lectures from Wolfgang Wagner

Top Analyses at ICHEP

- **Not enough luminosity yet!**
  - **Solidify analyses**
  - **Look for good candidates in dilepton (ee,eμ,μμ) and lepton+jets (ej,μj) channels**
  - **Check background description**

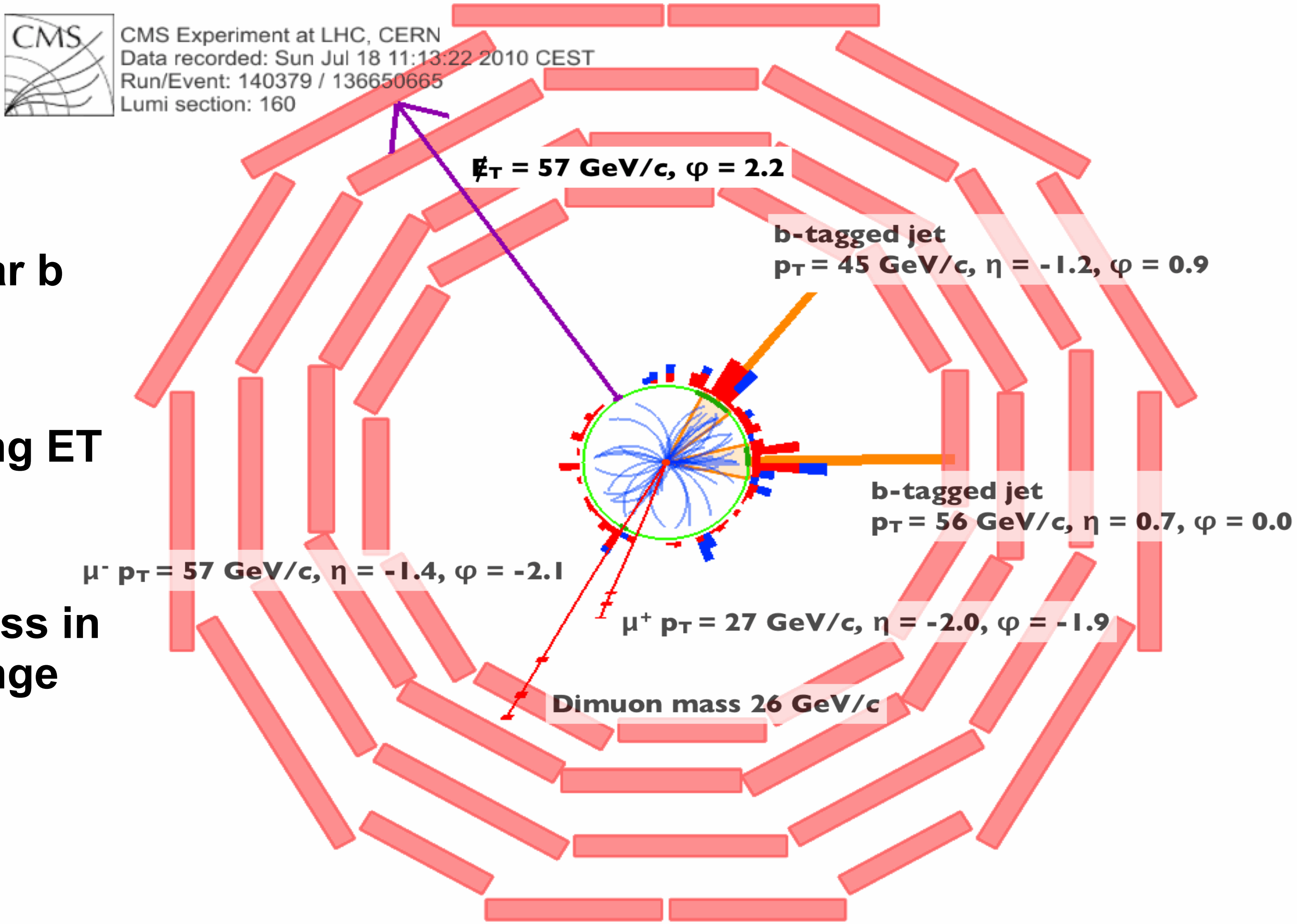




Top candidate events: ATLAS: 2+7 = 9
(dilepton & lepton+jets) **CMS: 2+3 = 5**

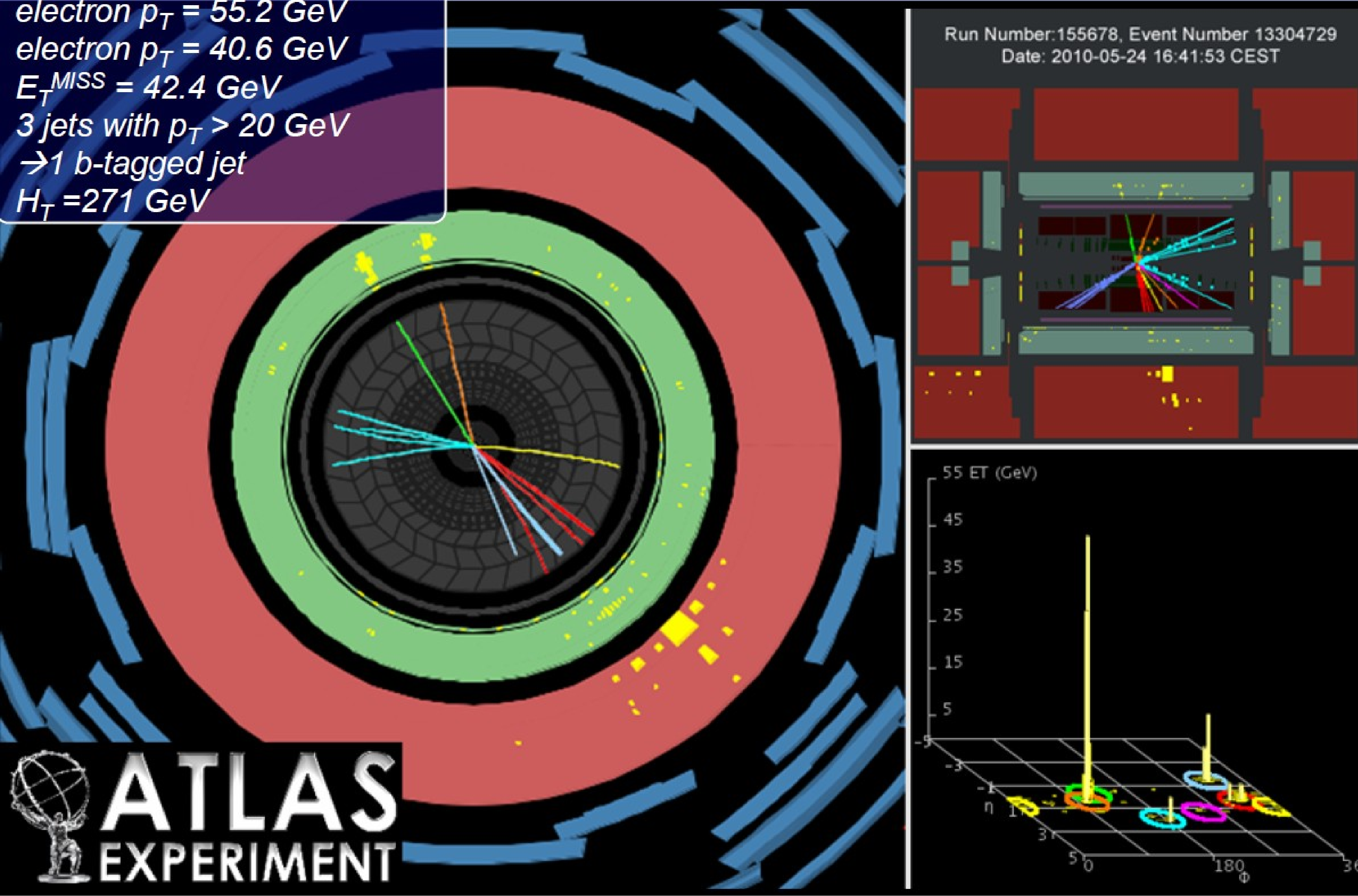
Top Pair Candidate in μμ Channel

- Event passes full selection:
  - Two muons with opposite charge
  - Two jets with clear b tags & secondary vertices
  - Significant missing ET (> 50 GeV)
  - Preliminarily reconstructed mass in 160 – 220 GeV range



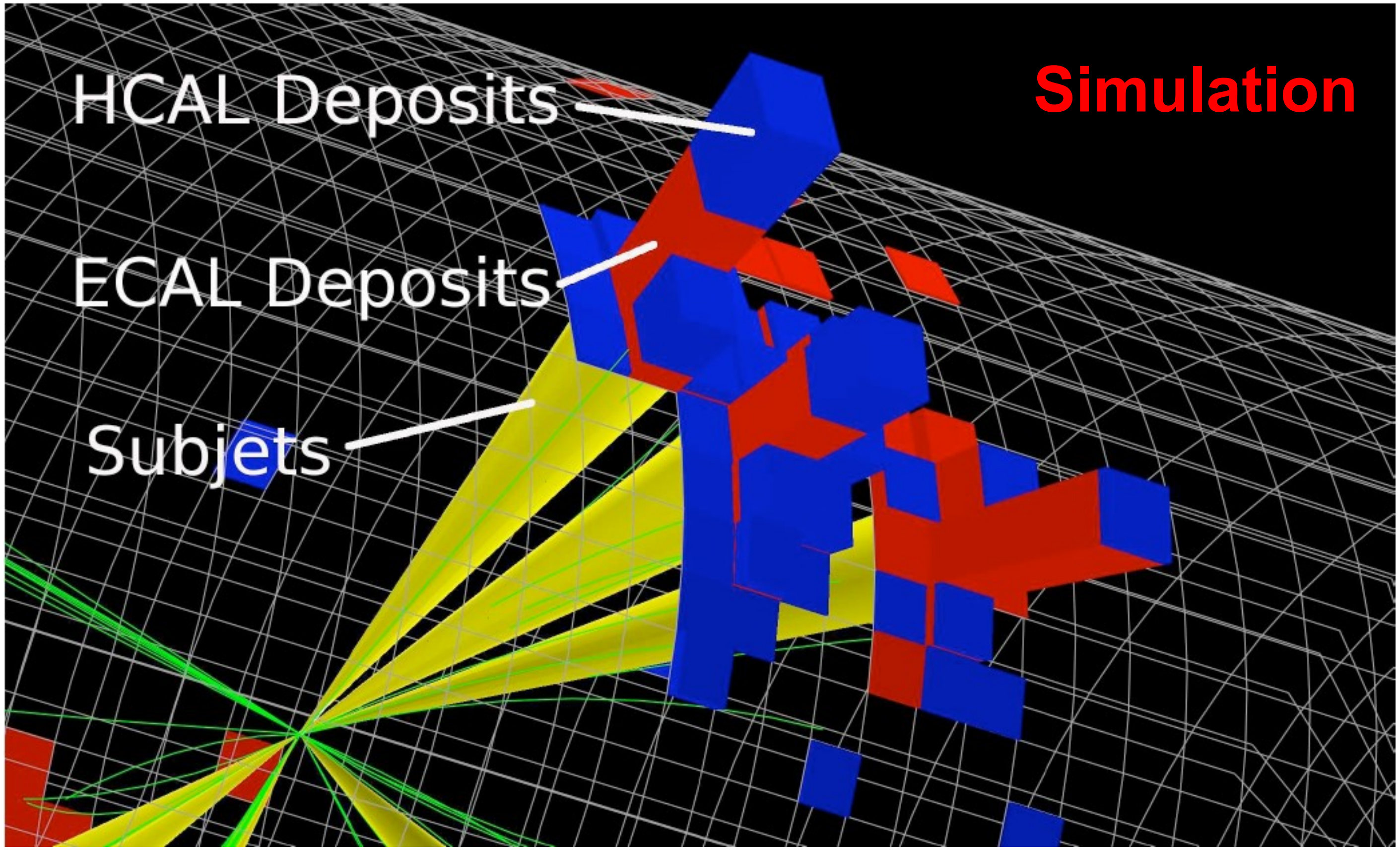
Top pair candidate in ee channel

electron p_T *= 55.2 GeV*
electron p_T *= 40.6 GeV*
E_T^{MISS} *= 42.4 GeV*
3 jets with p_T *> 20 GeV*
→1 b-tagged jet
H_T *=271 GeV*



Boosted Tops

- Example analysis looking for top jets with p_T of >≈ 600 GeV in signal sample Z' → ttbar → hadr. with $M_{Z'}$ = 2 TeV vs. QCD jets at similar p_T
- Use Cambridge/Aachen algorithm to resolve subjets, R = 0.8
- Gain stat. from ≈ 68% of hadr. W decays
- Efficiency for top jets: **46%**
- Reject non-top jets: **98%**
- Example has 800 GeV



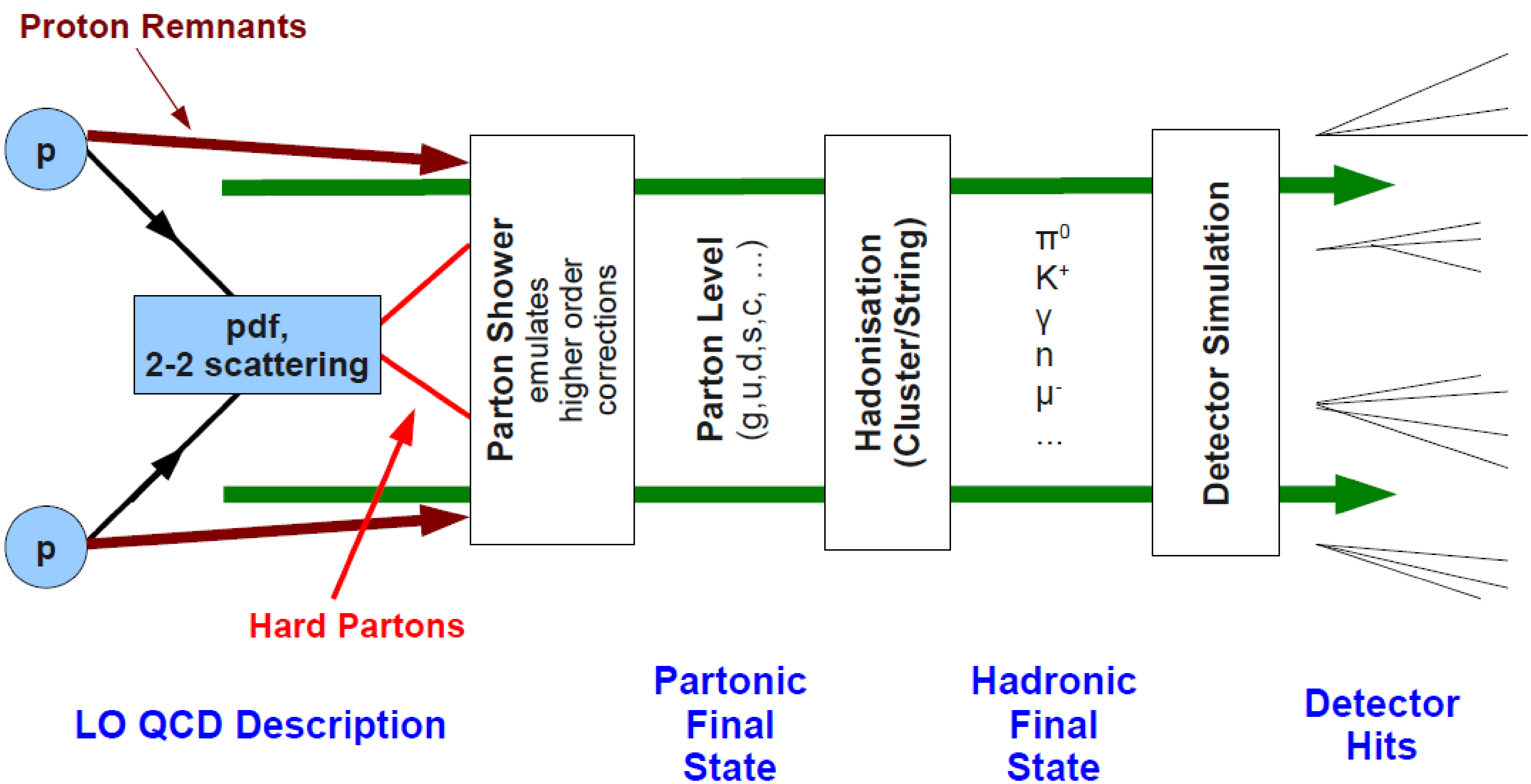
Kaplan et al., PRL101, 2008
CMS PAS JME-09-001

Outlook

- What will we learn from LHC?
- LHC is a superb laboratory to investigate jet and weak boson production
- The first top's have been sighted this side of the Atlantic
- After four months we start beating Tevatron limits
- Unknown territory is explored in the Standard Model …
- and beyond ?

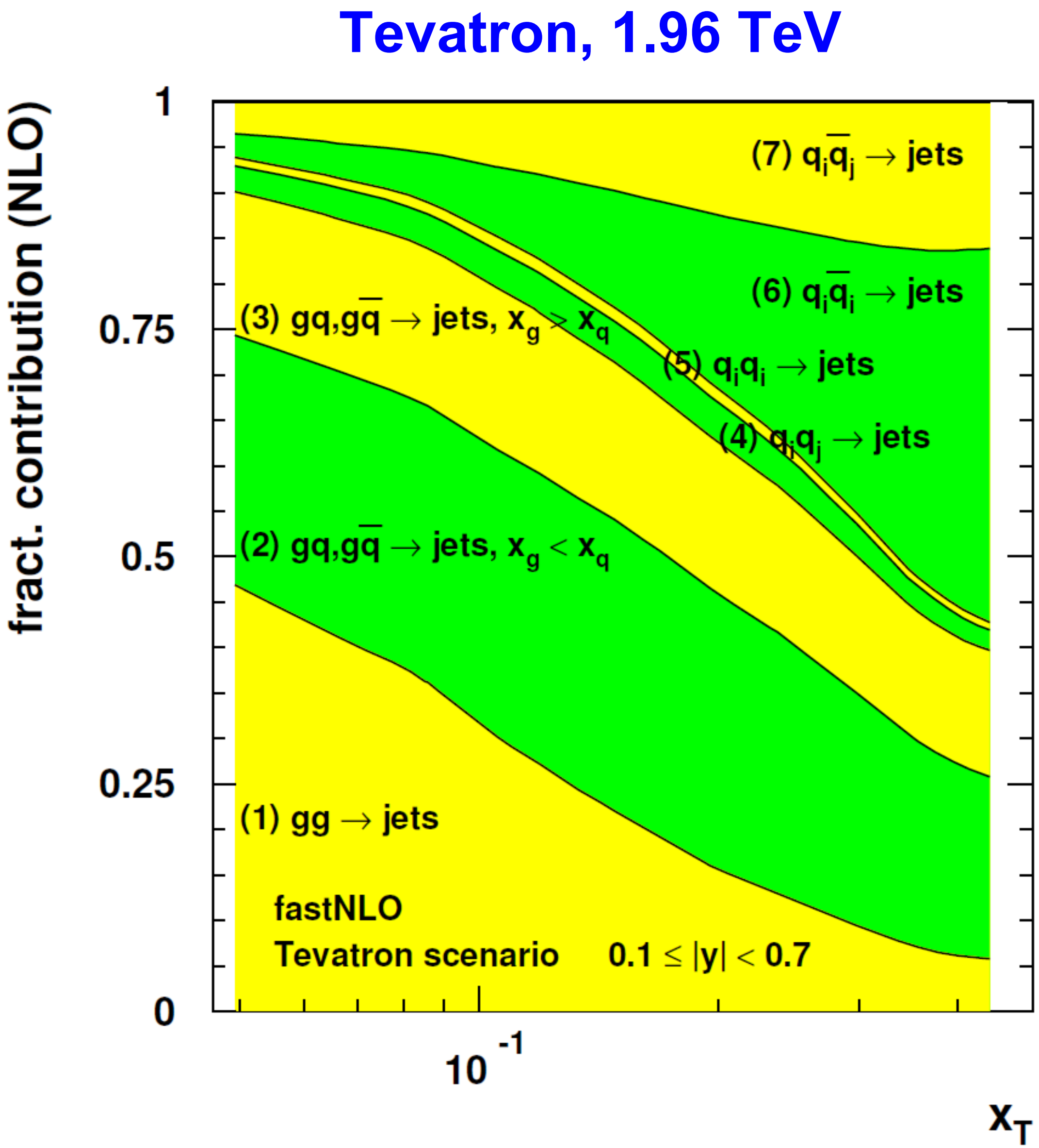
Backups

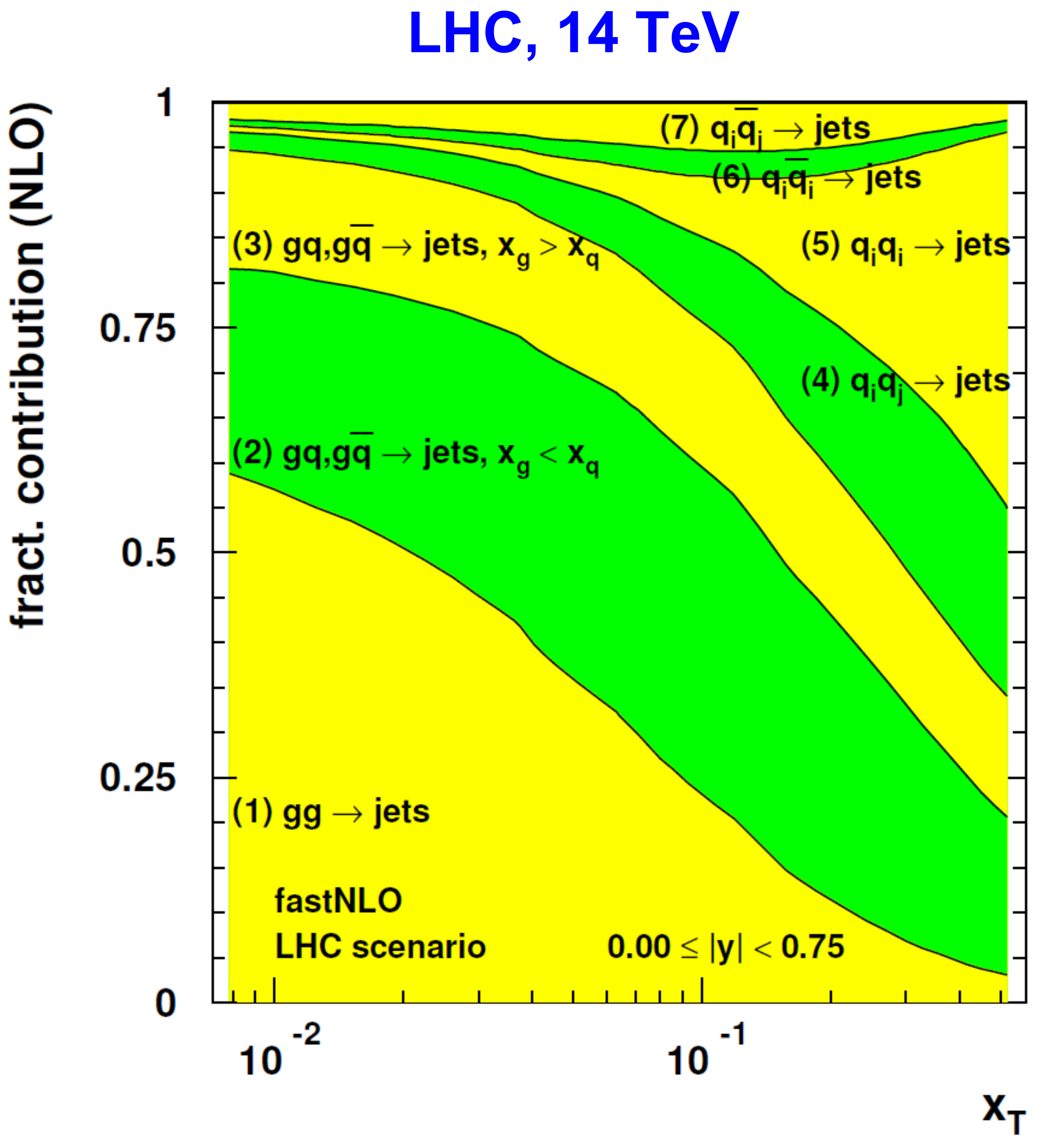
MC Event Generation Steps



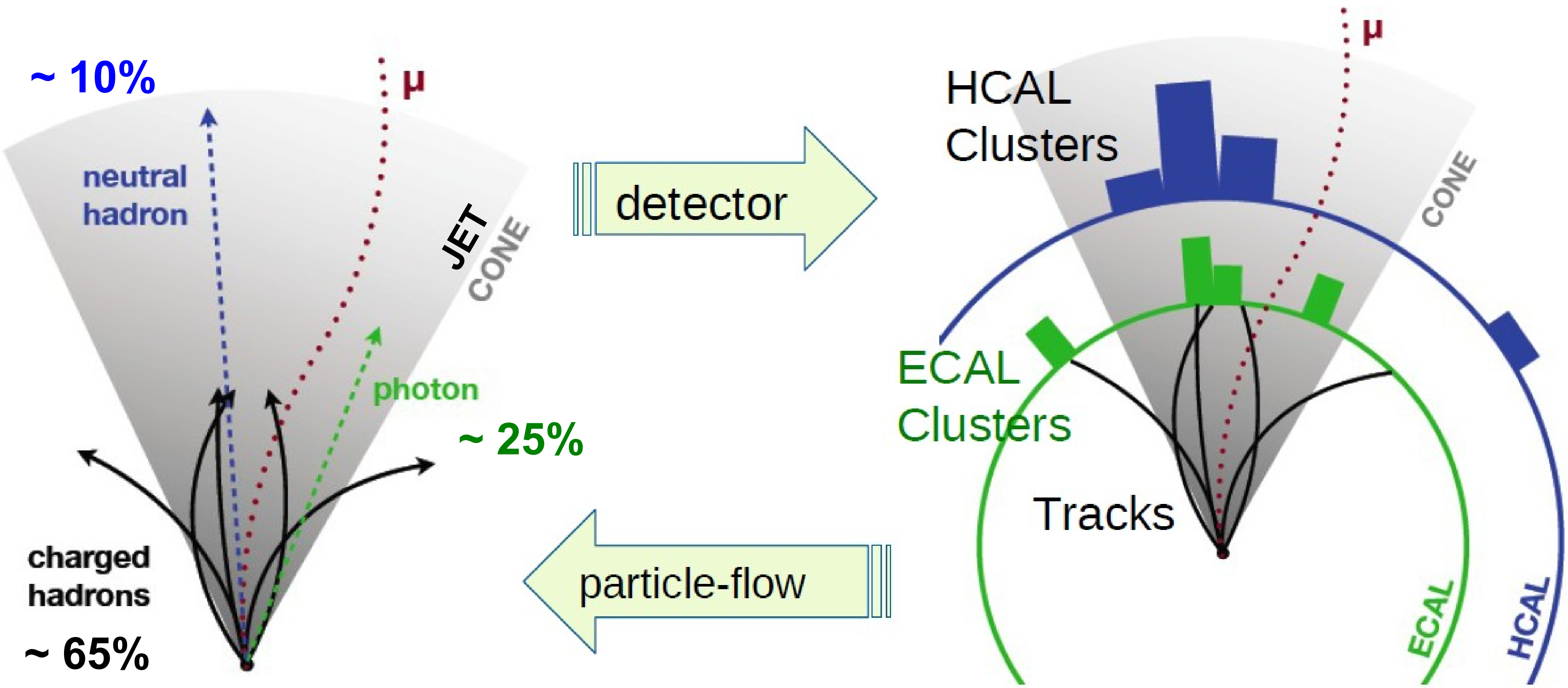
A. Oehler

Jet Cross Section Decomposition





Particle Flow Concept



Associate particle types to all measurements, apply type-dependent corrections

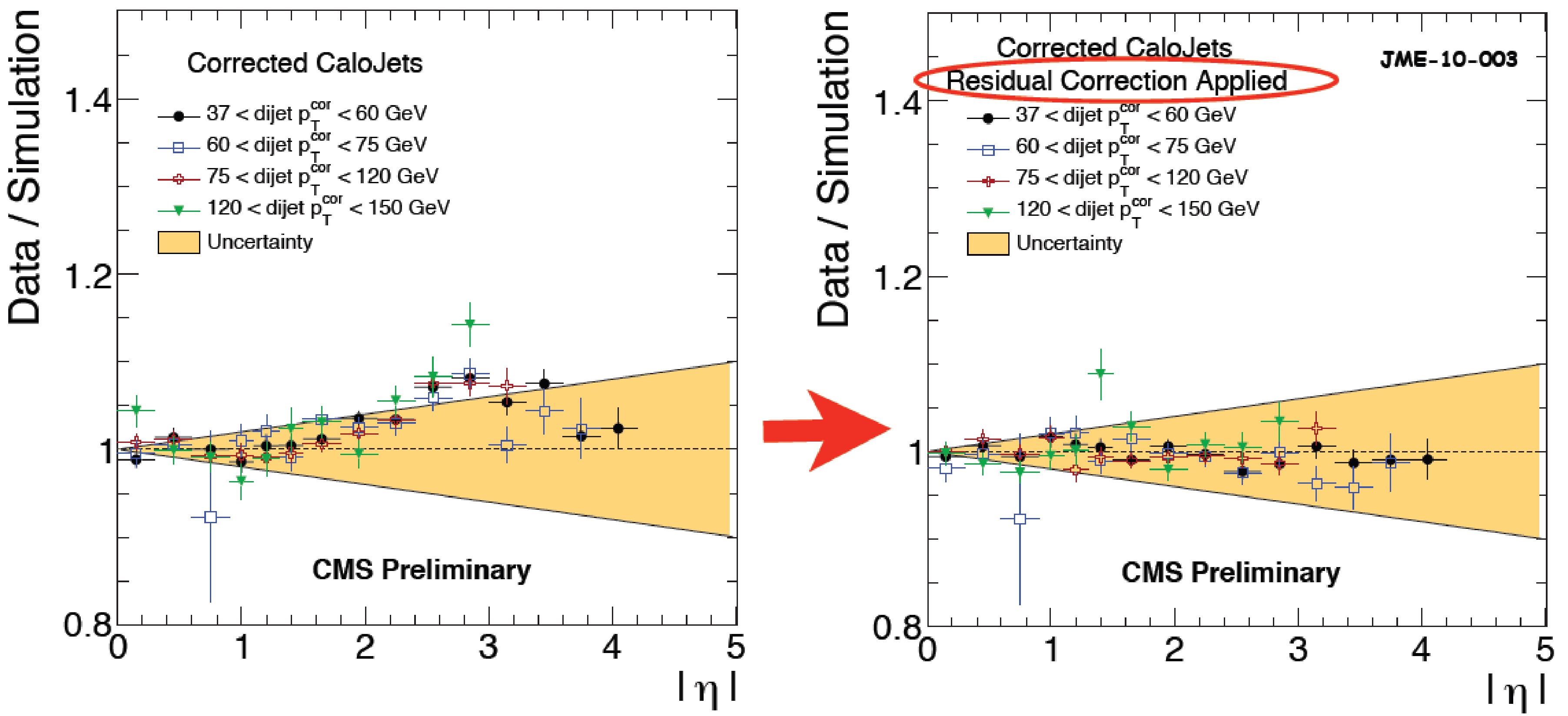
Relative Jet Corrections

- Response rapidity dependence is extracted from dijet asymmetry

M. Voutilainen, ICHEP2010

- Residual correction is applied for inclusive jets, other studies are covered by the systematic uncertainty band of **2% times unit of rapidity**

Jet correction = Absolute(p_T) [MC] × Relative(η) [MC+data]



Jet Calibration and Uncertainty

Jet calibration:

Simple $P_{T,jet}$ and y dependent correction applied to measured jets at the electro-magnetic scale.
Using particle level (truth) from Monte Carlo simulation as reference.

Jet energy scale uncertainty:

Evaluated using MC using various detector configurations, hadronic shower and physics models
Based on large test-beam experience.

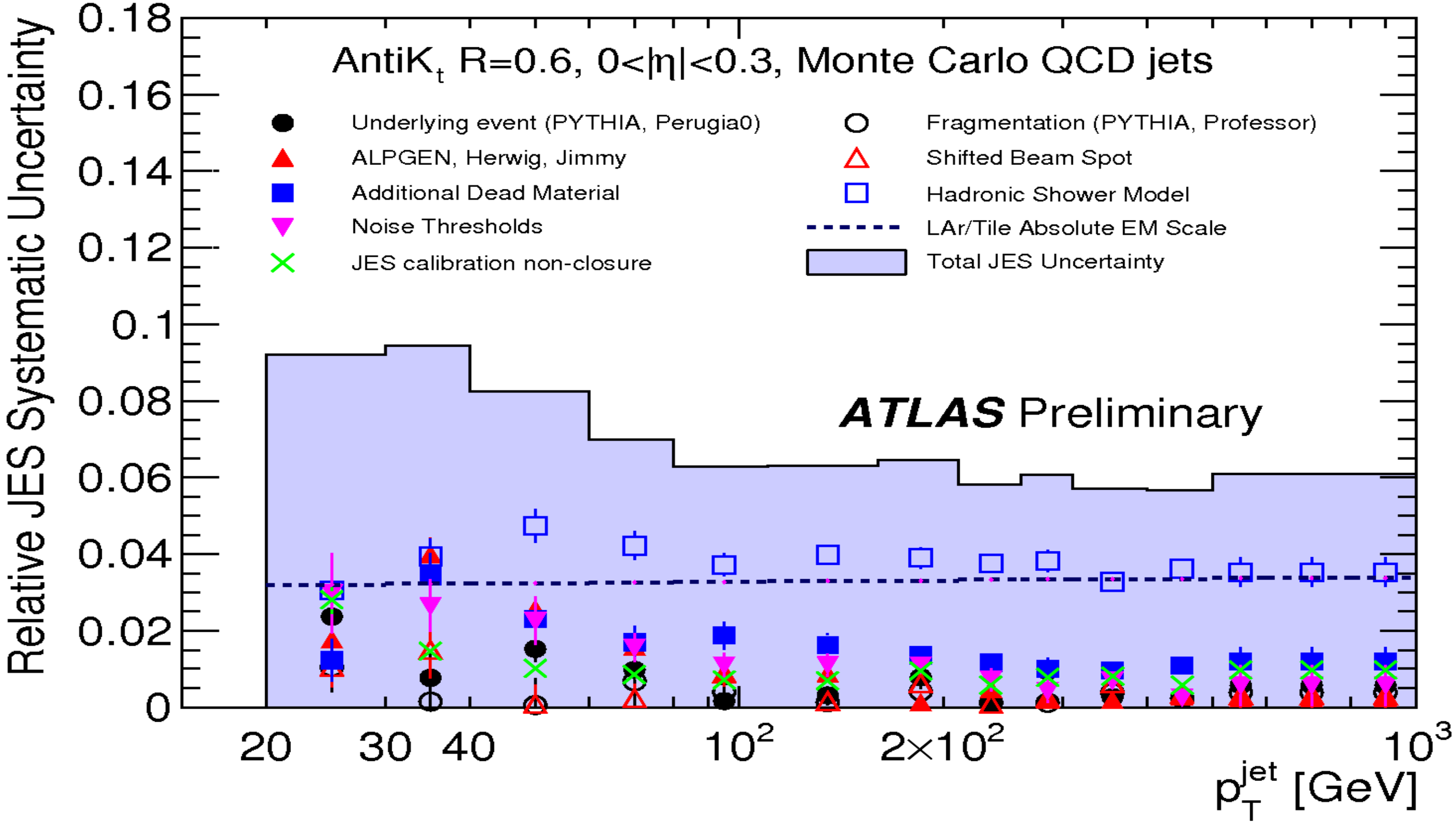
Example:

In-situ measurements:

1) Using Di-jet balance to transport uncertainty central -> forward

2) Additional uncertainty for pile-up from average tower energy per vertex

3) Cross-checked with single isolated hadron response measurement (E_{calo}/p_{track})
Uncertainty via: deconvolution of jets in individual particles

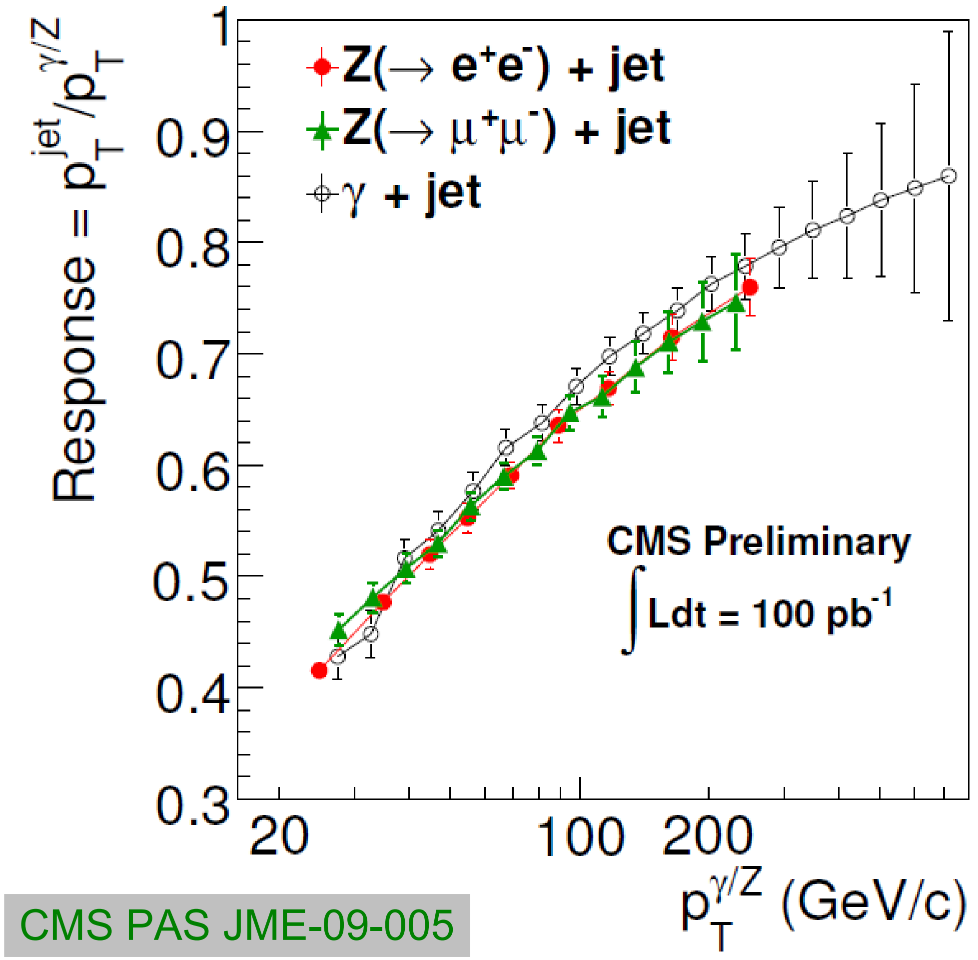


Jet energy scale uncertainty smaller than 7% for $p_{t,jet}$>100 GeV

Absolute Correction (Simulation Result)

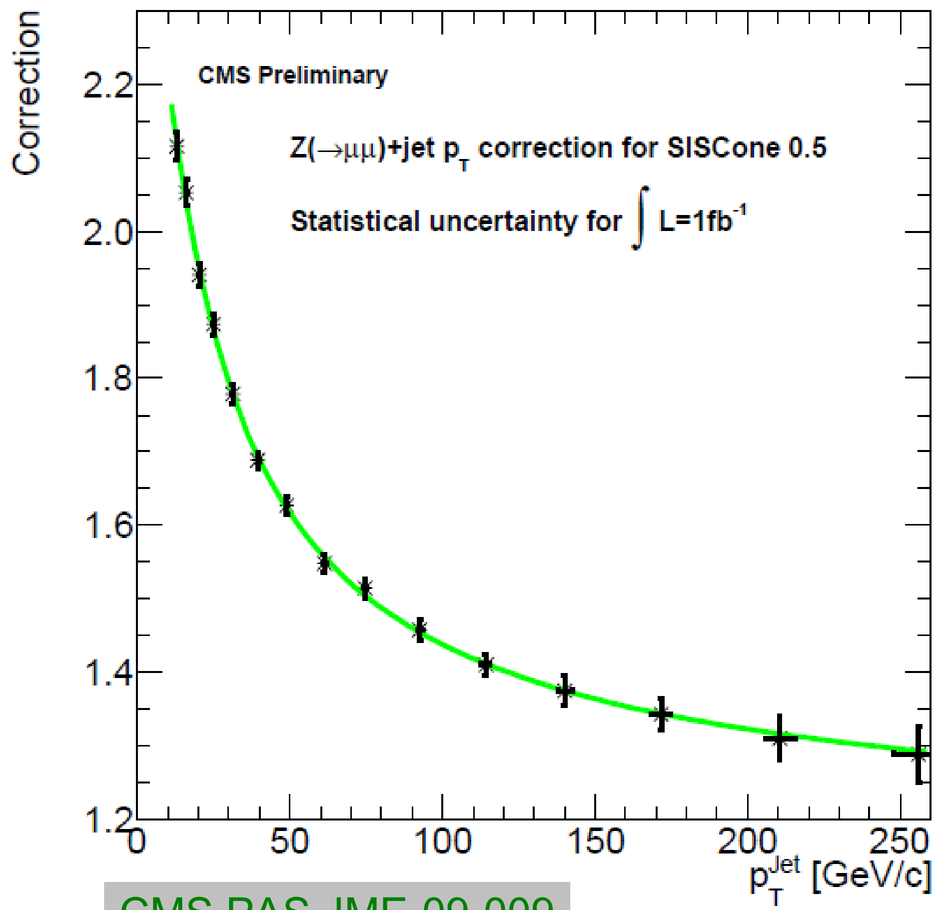
CMS detector simulation, calorimeter towers, E_{CMS} = 10 TeV

Comparison of jet responses



CMS PAS JME-09-005

Derived correction at the example of $Z(\rightarrow\mu\mu)$ + 1jet



CMS PAS JME-09-009

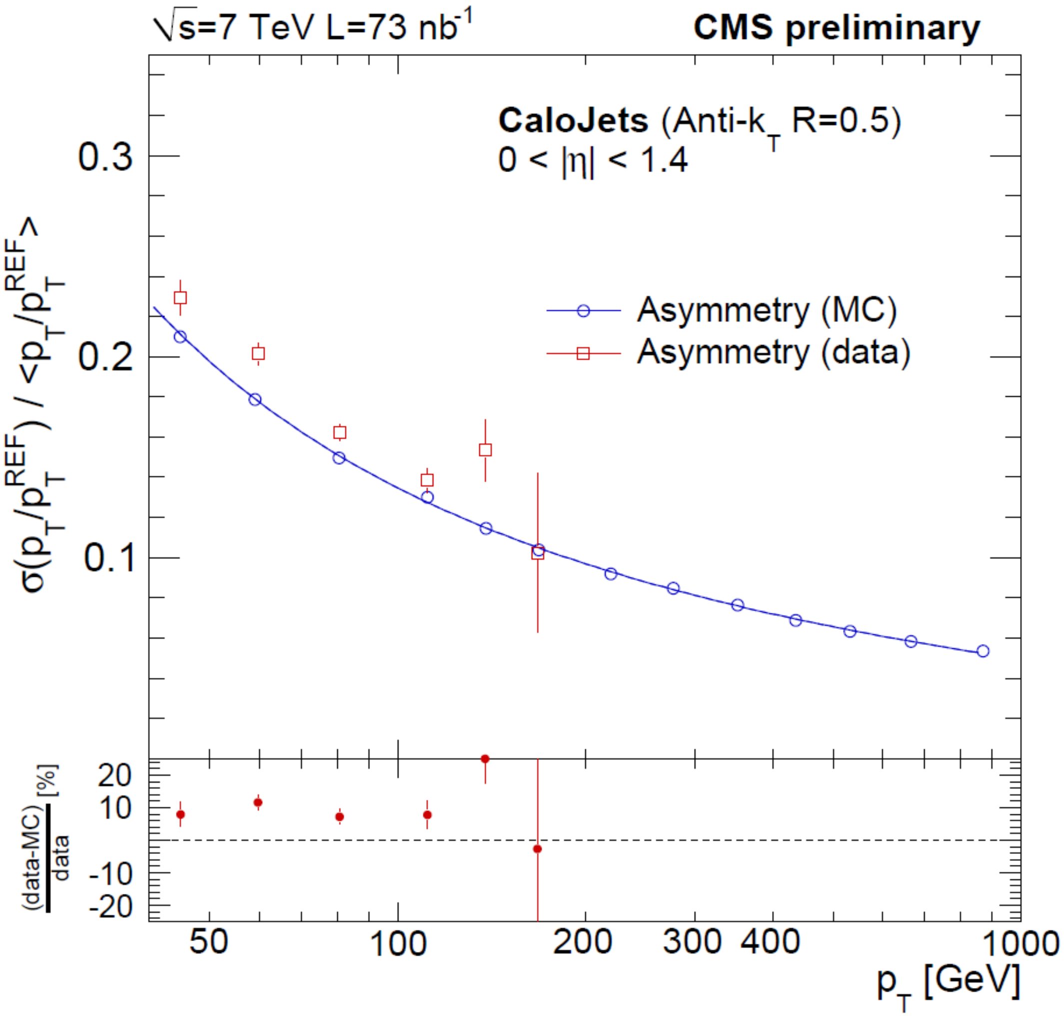
Jet Energy Resolution

Jet energy resolution (JER):

- Can be measured from data using Asymmetry Method used:
  For dijet events:

$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})} \Rightarrow \left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{2}\sigma_A$$

  Used at Tevatron.
- Comparison using MC information (matched jets) gives consistent results

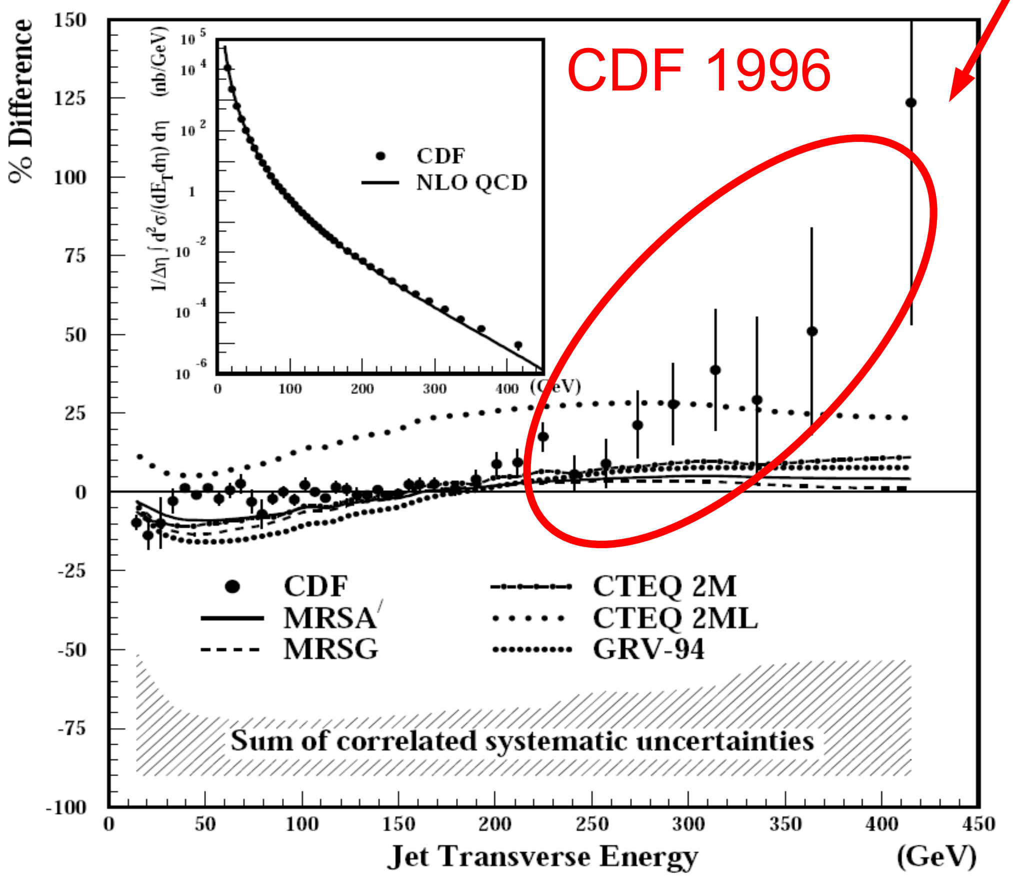


CMS PAS JME-10-003

Parton Density Experience

"The data are compared with QCD predictions for various sets of parton distribution functions.
The cross section for jets with E_T>200 GeV is significantly higher than current predictions based on $O(\alpha_s^3)$ perturbative QCD calculations. ..."

Phys.Rev.Lett. 77 (1996)

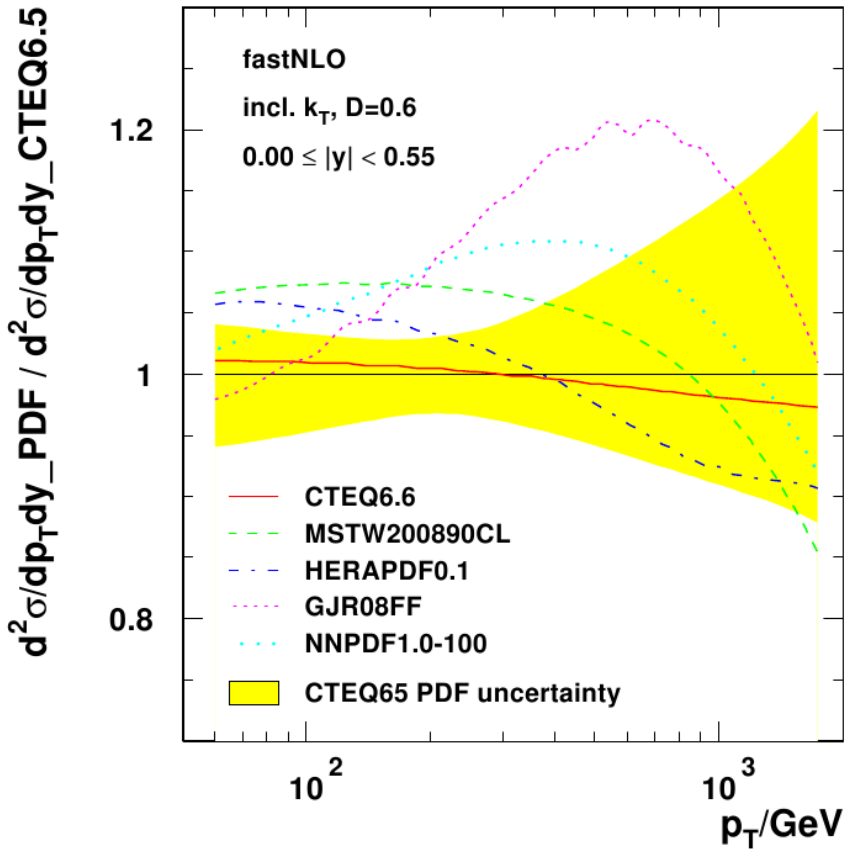


Explained by change in gluon density which then can be constrained by jets!

Today:

Much better estimates of PDF uncertainties

But beware ...



W/Z Systematic Uncertainties

CMS electron channels

Source	W channel (%)	Z channel (%)
Electron reconstruction/identification	6.1	7.2
Trigger efficiency	0.6	-
Isolation efficiency	1.1	1.2
Electron momentum scale/resolution	2.7	-
$\not{E}_T$ scale/resolution	1.4	-
Background subtraction	2.2	-
PDF uncertainty in acceptance	2.0	2.0
Other theoretical uncertainties	1.3	1.3
TOTAL (without luminosity uncertainty)	7.7	7.7
Luminosity	11.0	11.0

W7Z Signal & Background Expectations

Electron channels

Channel	$\sigma(\times B_r)$	ε_{filter}	N_{evt} $(\times 10^3)$	$\mathscr{L}$ (pb^{-1})
$W \to e\nu$	20510 pb	0.63	140	11
$\gamma/Z \to ee, \sqrt{\hat{s}} > 60$ GeV	2015 pb	0.86	399	230
$\gamma/Z \to ee, \sqrt{\hat{s}} < 60$ GeV	9220 pb	0.022	197	969
$W \to \tau\nu_\tau$	20510 pb	0.20	32	8
$Z \to \tau\tau$	2015 pb	0.05	13	129
$t\bar{t}$	833 pb	0.54	382	850
Inclusive jets (p_T >6 GeV)	70 mb	0.058	2480	0.0006
Inclusive jets (p_T >17 GeV)	2333 μb	0.09	3725	0.02
WW$\to (e\nu)(e\nu)$	1.275 pb	1.	20	15608
ZZ	14.8 pb	1.	43	2922
WZ	29.4 pb	1.	50	1699

ATLAS, CERN-OPEN-2008-020

Channel	$\sigma(\times B_r)$	ε_{filter}	N_{evt} $(\times 10^3)$	$\mathscr{L}$ (pb^{-1})
$W \to \mu\nu$	20510 pb	0.69	190	13
$\gamma/Z \to \mu\mu, \sqrt{\hat{s}} > 60$ GeV	2015 pb	0.89	446	249
$W \to \tau\nu_\tau$	20510 pb	0.20	32	8
$Z \to \tau\tau$	2015 pb	0.05	13	129
$t\bar{t}$	833 pb	0.54	382	850
$b\bar{b} \to \mu + X$	766 μb	2.1×10^{-4}	110	0.67
$b\bar{b} \to \mu\mu + X$	25 μb	1.6×10^{-4}	140	35

Muon channels

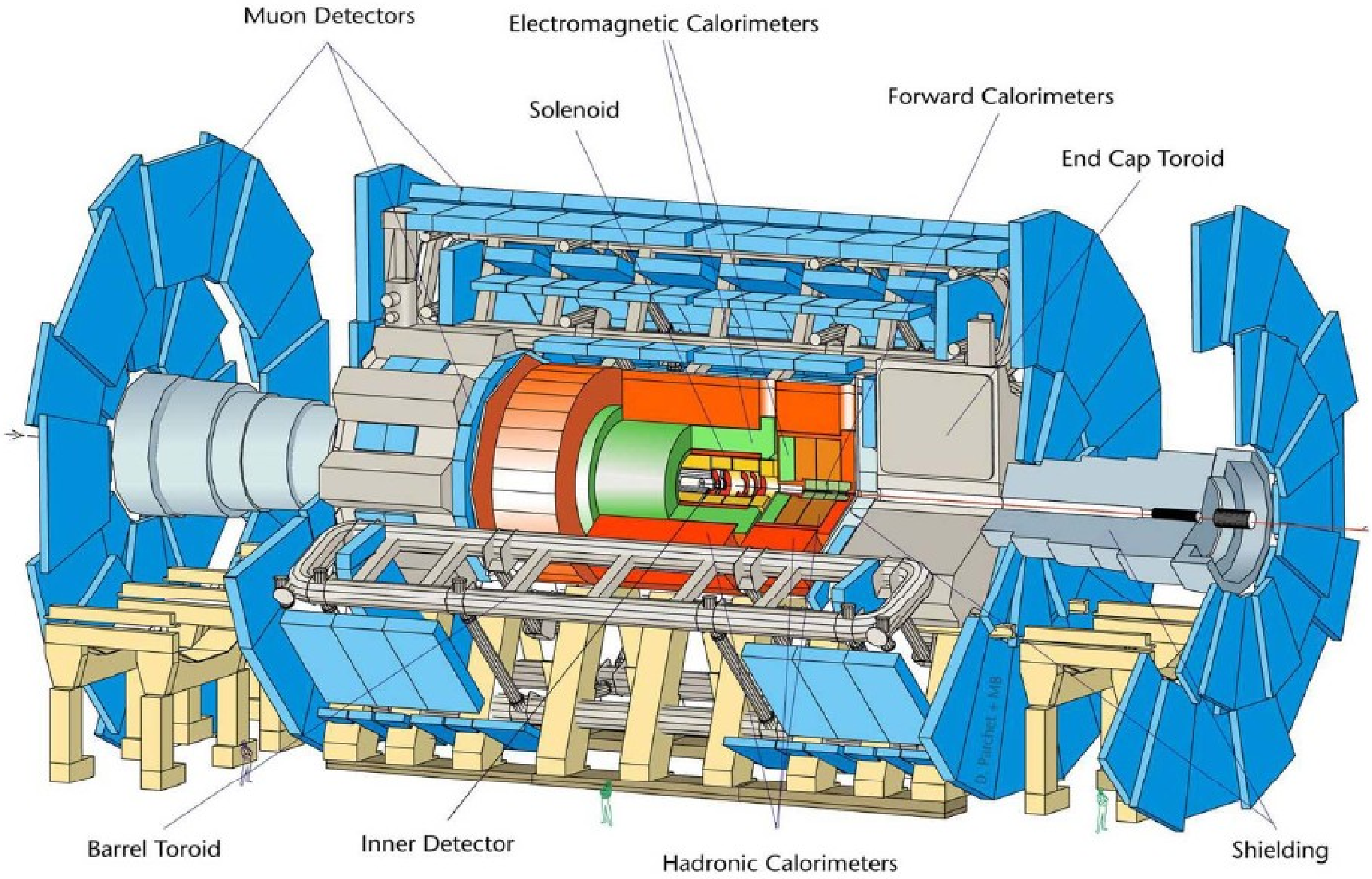
The ATLAS Detector

Inner Detector (ID) tracker:
- Si pixel and strip + transition rad. tracker
- $\sigma(d_0)$ = 15µm@20GeV
- $\sigma/p_T \approx 0.05\% p_T \oplus 1\%$

Calorimeter
- Liquid Ar EM Cal, Tile Had.Cal
- EM: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
- Had: $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$

Muon spectrometer
- Drift tubes, cathode strips: precision tracking +
- RPC, TGC: triggering
- $\sigma/p_T \approx$ 2-7%

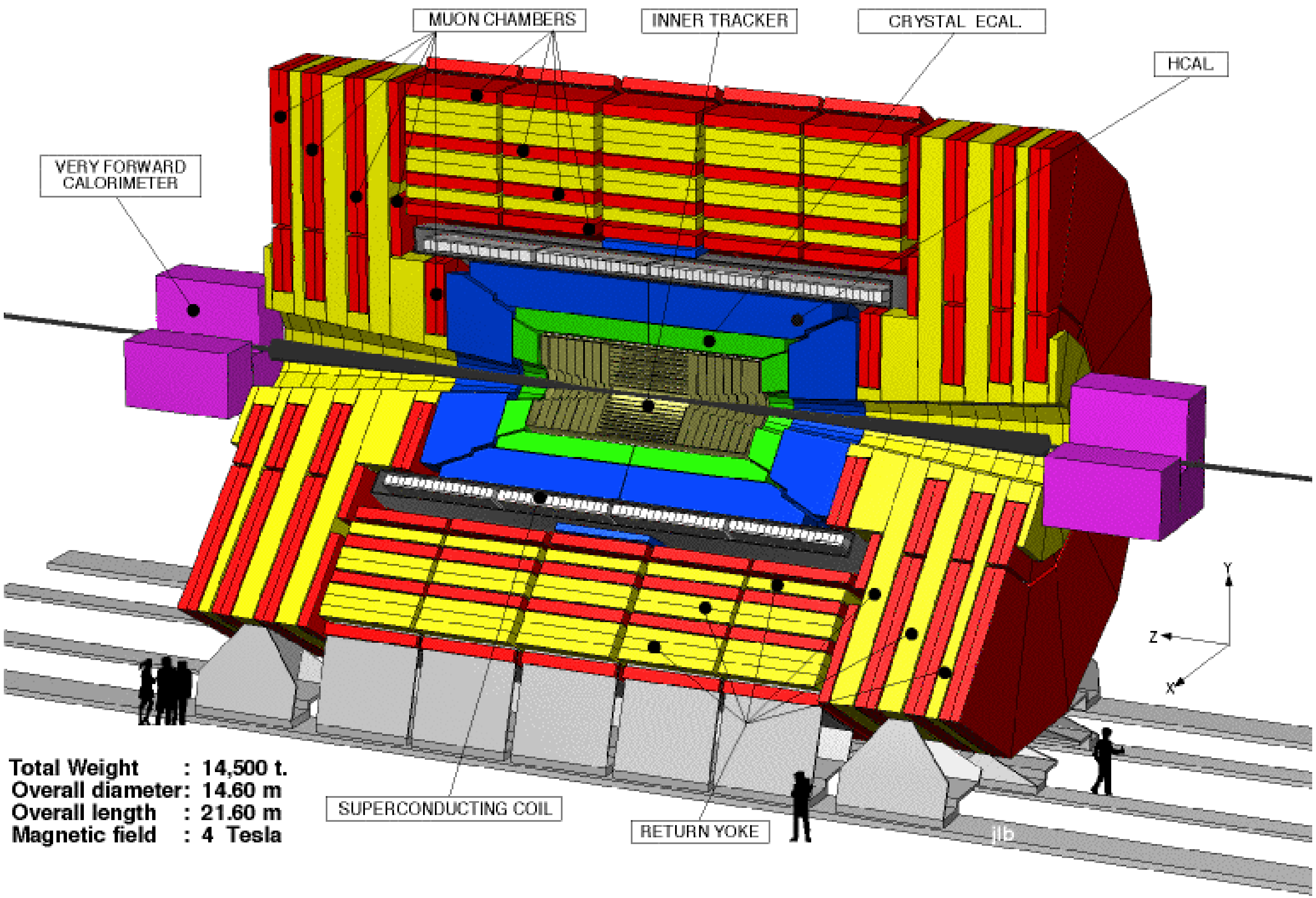
Magnets
- Solenoid (ID) → 2T
- Air toroids (muon) → up to 4T



Full coverage for $|\eta|<2.5$, calorimeter up to $|\eta|<5$

See also JINST 3 2008 S08003

The CMS Detector



Inner detector (tracker):

- Si pixel & strip tracker
- $\sigma/p_T \approx$ 1-2% (μ at 100 GeV)

Calorimeter:

- PbWO4 crystal ECAL, brass/scintillator HCAL
- ELM: $\sigma_E/E = 2.8\% /\sqrt{E} + 0.3\%$
- HAD: $\sigma_E/E = 100\% /\sqrt{E} + 5\%$

Muon system:

- Drift tubes, cathode strips, resistive plate chambers
- $\sigma/p \approx$ 10 – 50% (muon alone)
- $\approx$ 0.7 – 20% (with tracker)

Magnet:

- Solenoid → 3.8T

See also:
PTDR I LHCC-2006-001,
JINST 3 2008 S08003

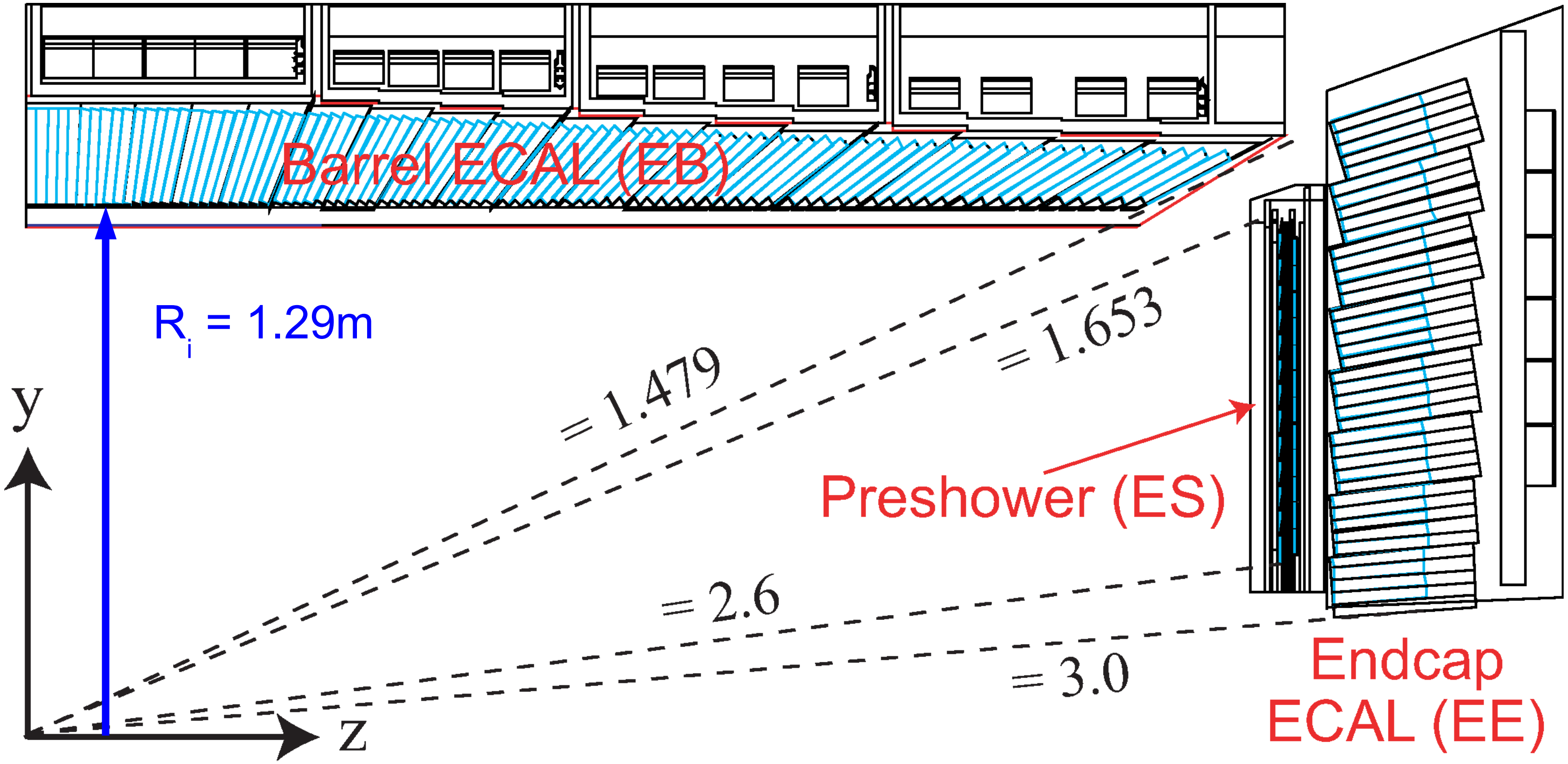
Electromagnetic Calorimeter

Barrel (EB):
- η segments: 2x85
- φ segments: 360

→ 61200 crystals ($PbWO_4$, 26 X_0)

→ Δη x Δφ ≈ 0.0174 x 0.0174

Segmentation



Energy resolution from test beam:

S = 2.8%, N = 120 MeV, C = 0.30%

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

Segmentation

Endcaps (EE):
- (x,y) grid on two halfs
- front face 28 x 28 mm^2

→ 2 x 2 x 3662 crystals = 14648 ($PbWO_4$, 25 X_0)

Hadronic Calorimeter

HCAL (tower structure):
- Barrel (HB): |η| < 1.4, 2592 towers
- Endcaps (HE): 1.3 < |η| < 3.0, 2592 "
- Outside coil (HO): |η| < 1.26, 2160 "

→ Depth (Brass abs. & plast. scint., ≈ 6 - 10 λ_N)

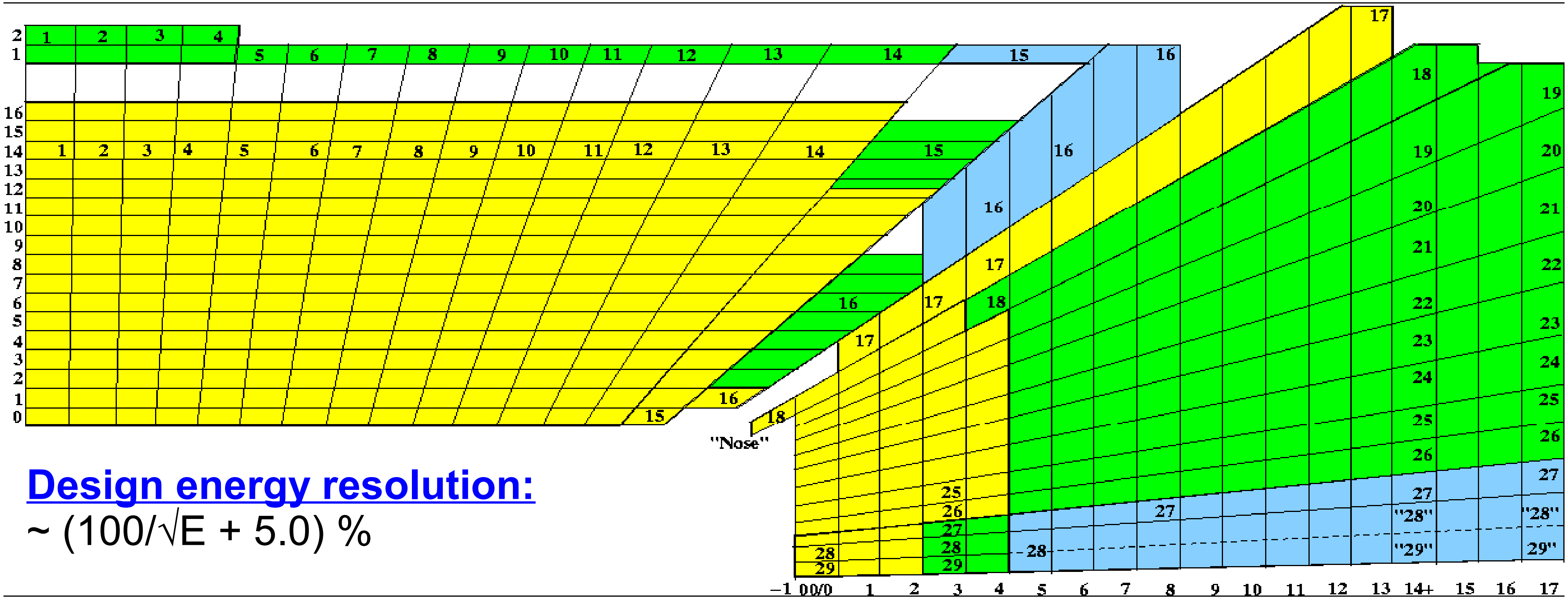
→ Δη x Δφ ≈ 0.087 x 0.087 → 0.350 x 0.175

- Forward (HF): 2.9 < |η| < 5.0 (not shown)

→ 2 x 864 towers (Brass,quartz fibers, ≈ 10 λ_N)

→ Δη x Δφ ≈ 0.111 x 0.175 → 0.302 x 0.350

CASTOR calorimeter (not shown):
- 5.1 < |η| < 6.5, ≈ 22 X_0, ≈ 10 λ_N



Design energy resolution:
~ (100/√E + 5.0) %