QCD at ATLAS

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University of Glasgow
(on behalf of the ATLAS Collaboration)

Quarks and Hadrons in strong QCD 17 - 20 March 2008 St. Goar, Germany

Outline:

I. Introduction: LHC and ATLAS

II. QCD Measurements:

a. Minimum bias events

b. Jets: inclusive jet cross section, di-jets, underlying event

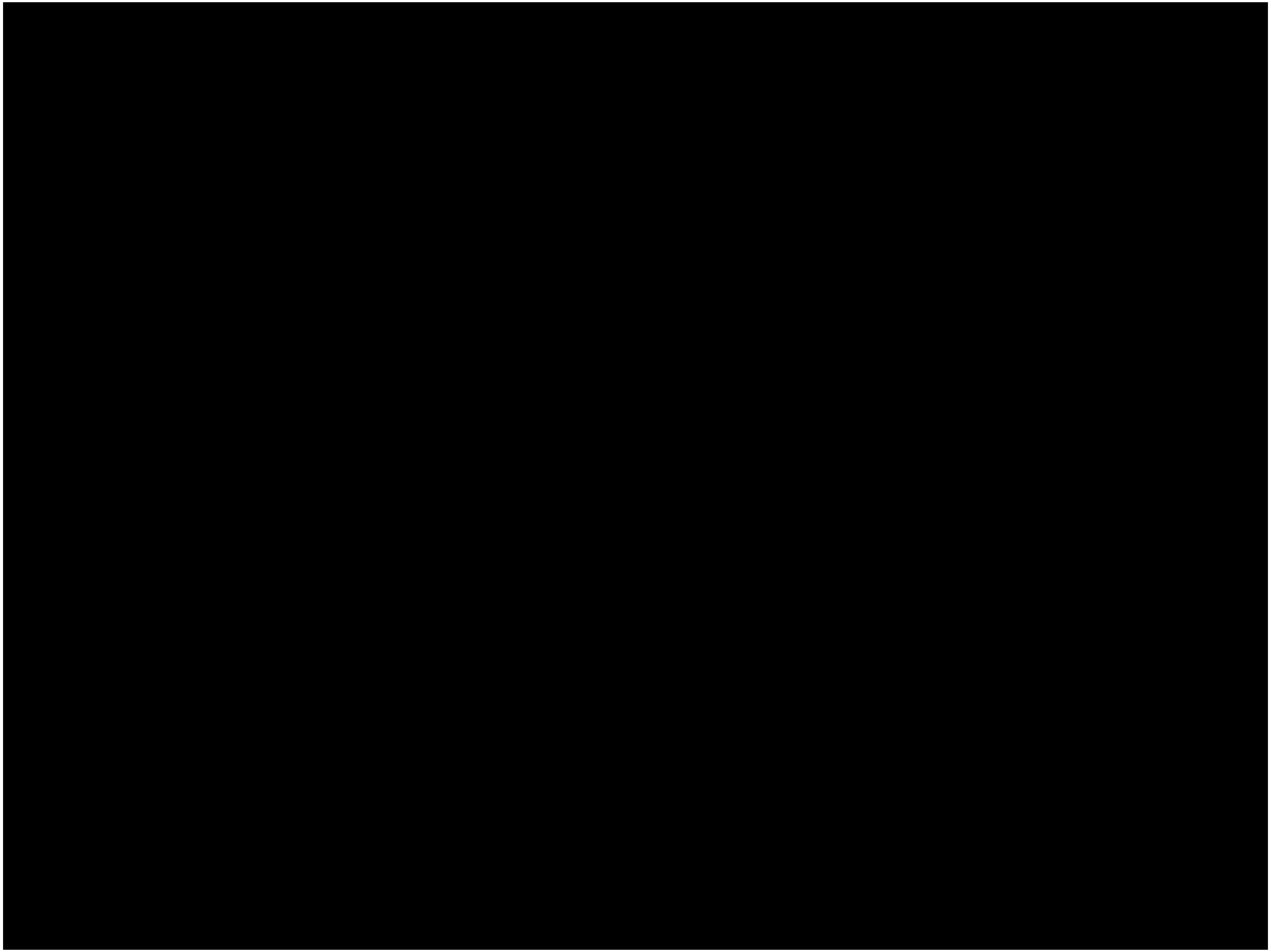
c. Parton luminosities and p.d.f.'s

d. Direct photon production

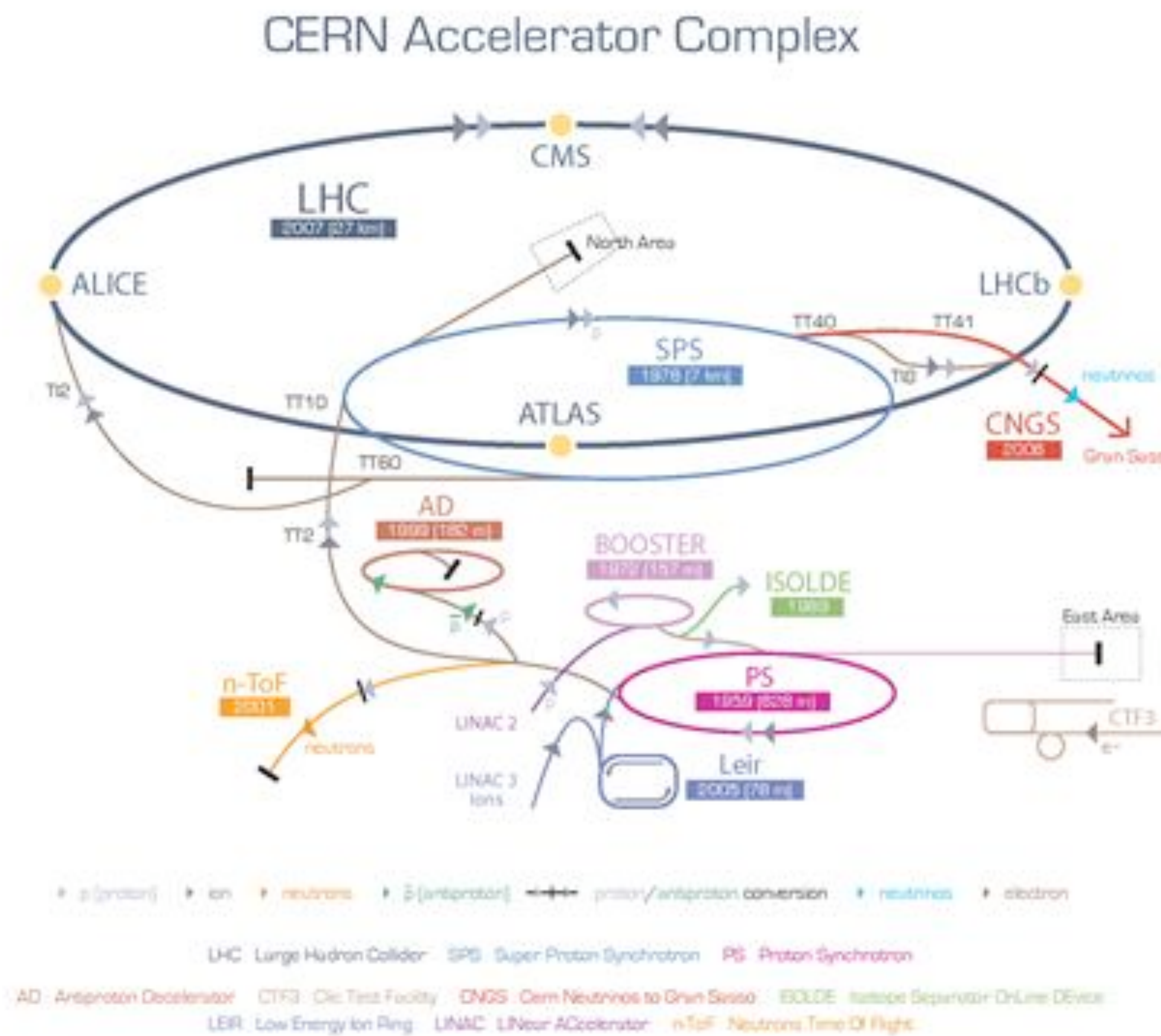
e. Measurement of the α_s at very large scales

f. Multi-parton interactions

III. Summary

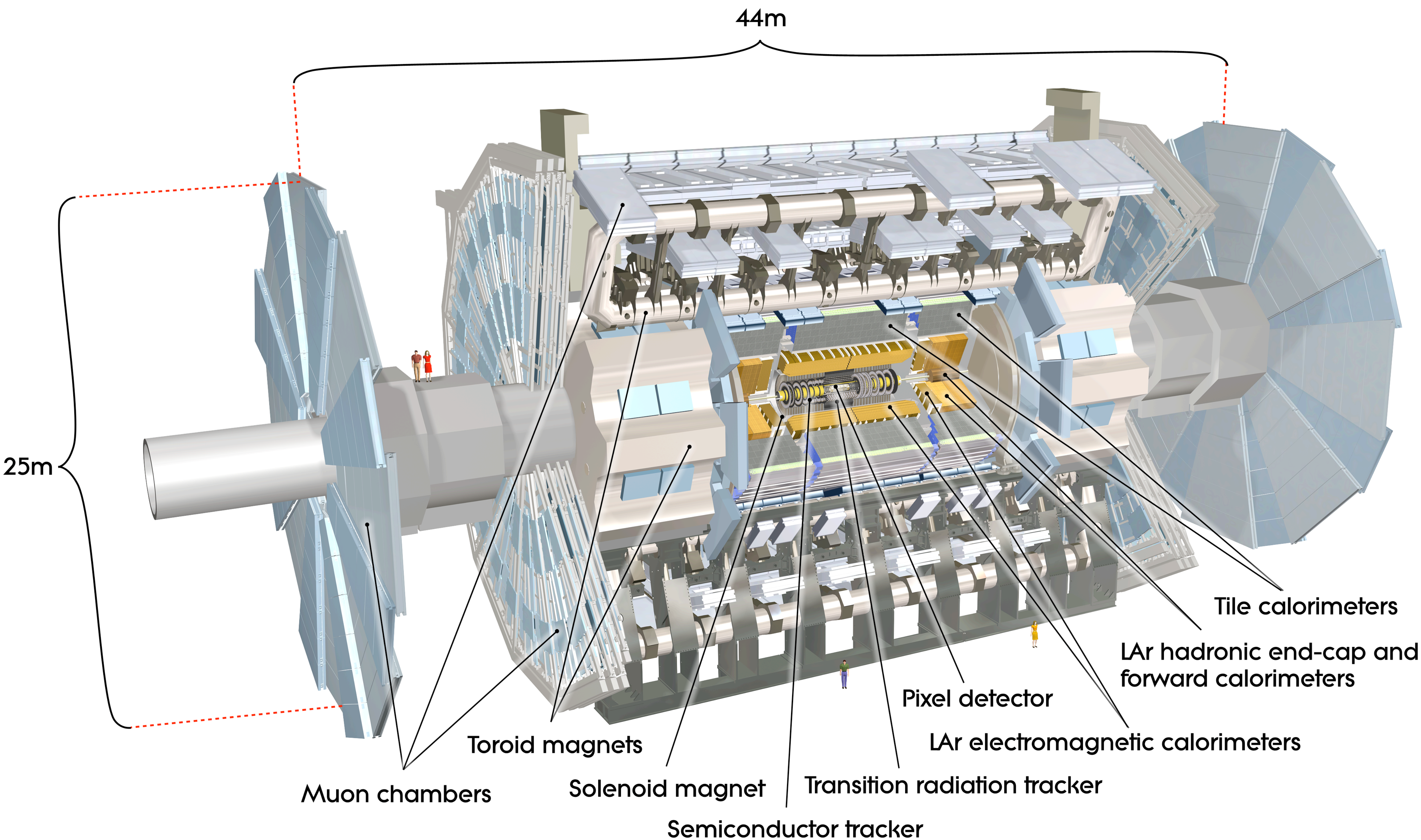


The *Large Hadron Collider*



- p-p collisions at $\sqrt{s}$=**14TeV** (x7 wrt Tevatron)
- design luminosity **10^{34} cm^{2}s^{-1}** (x100 wrt Tevatron)
- bunch crossing every 25 ns (**40 MHz**)
  - ~1fb^{-1}/year with L= 10^{32} cm^{2}s^{-1}
  - ~10 fb^{-1}/year with L= 10^{33} cm^{2}s^{-1}
- Current schedule:
  - End of May 2008: machine closed
  - End of June 2008: beam commissioning at 7TeV
  - **1-2 months of physics runs at 14TeV in 2008**
    - **aim for 10^{32} cm^{2}s^{-1} by the end of 2008 with ~100pb^{-1} integrated luminosity.**

ATLAS: *A* *T*oroidal *L*HC *A*pparatu*S*



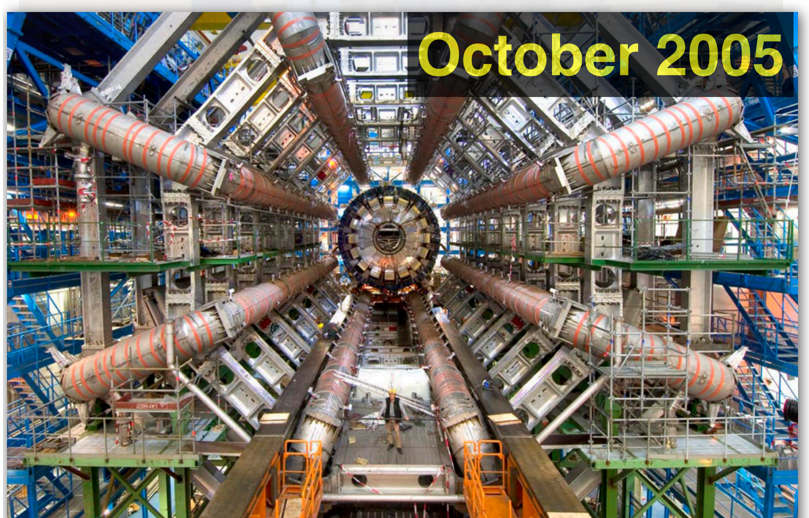
University of Glasgow

ATLAS Installation Progress


2003


October 2004


August 2005

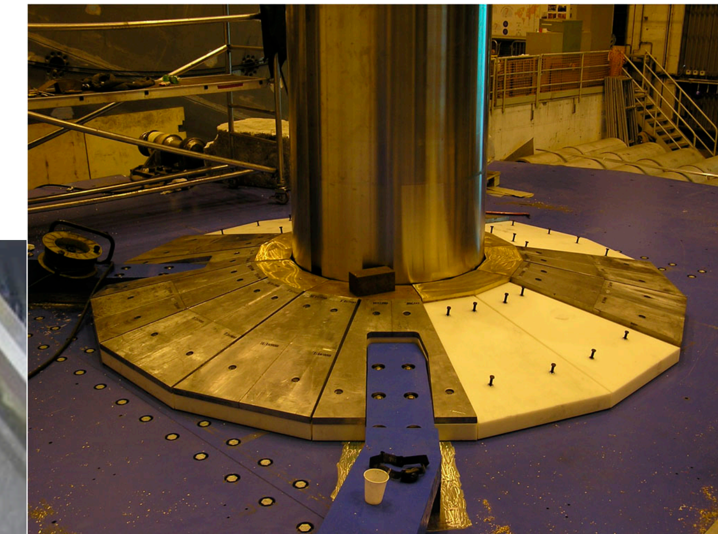

October 2005

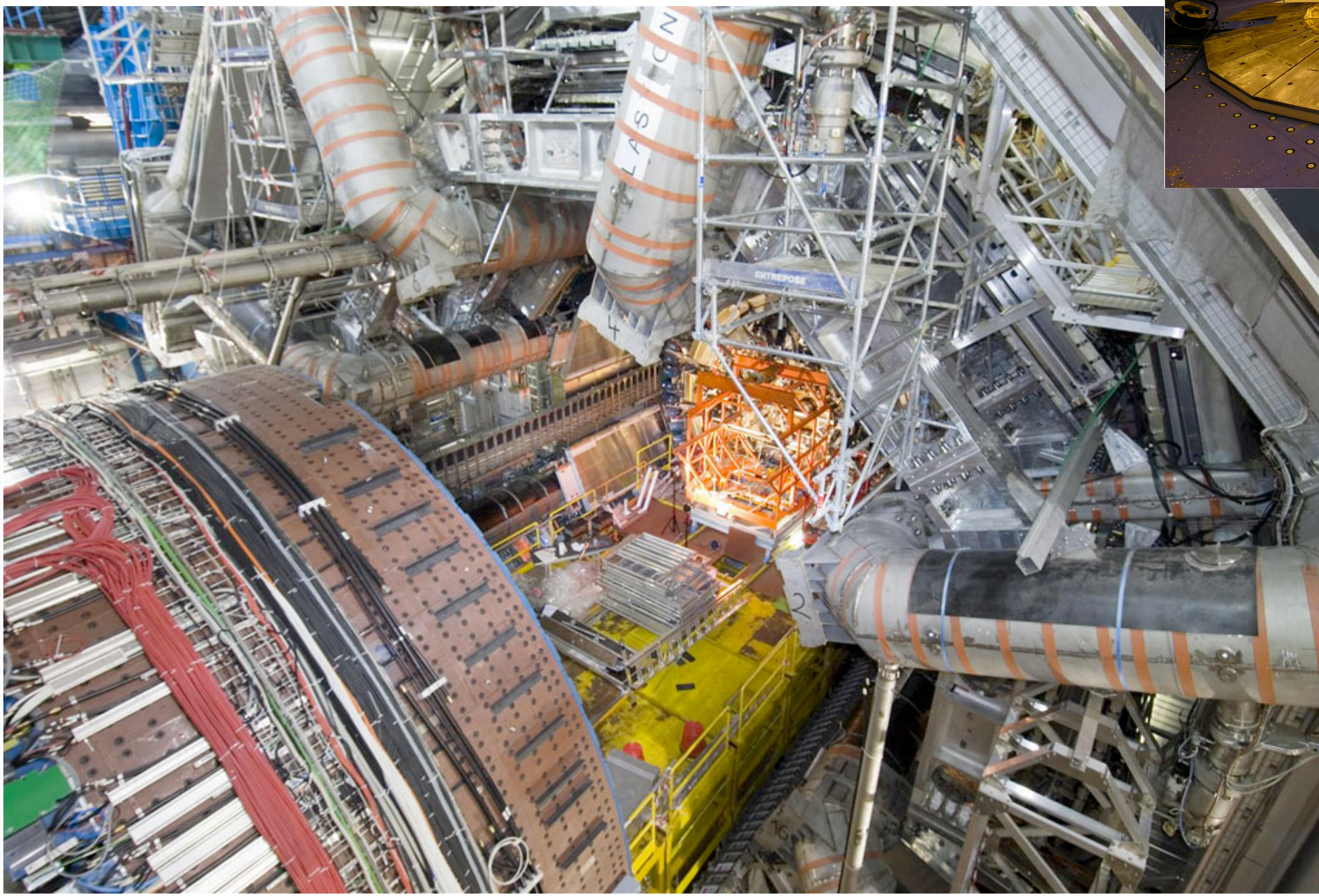

October 2006

November 2007

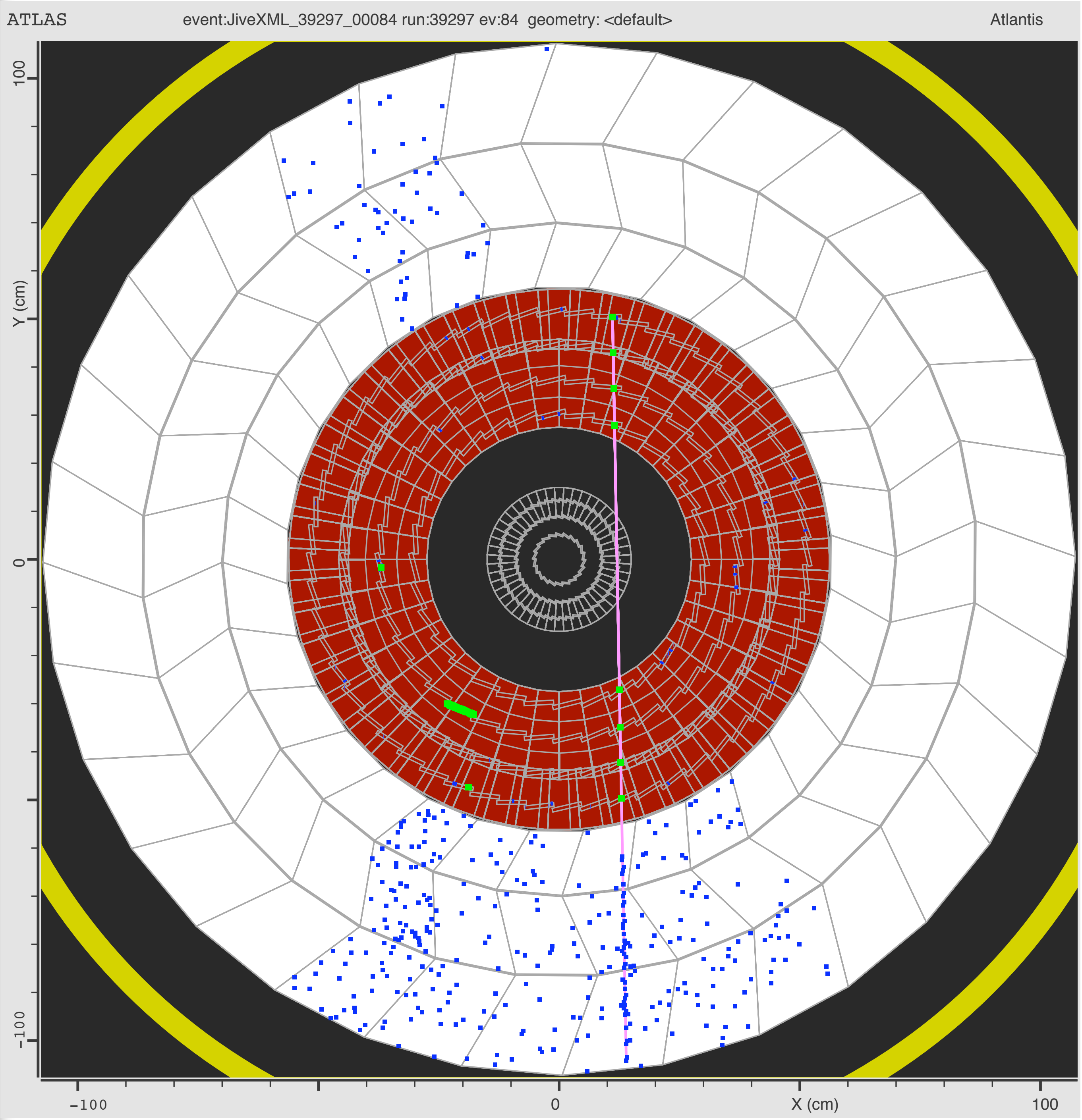
Status on 29th of February 2008!

- Last Large Piece of ATLAS Detector Lowered Underground: "small" wheels (~30ft in diameter and wheighs ~100tons)

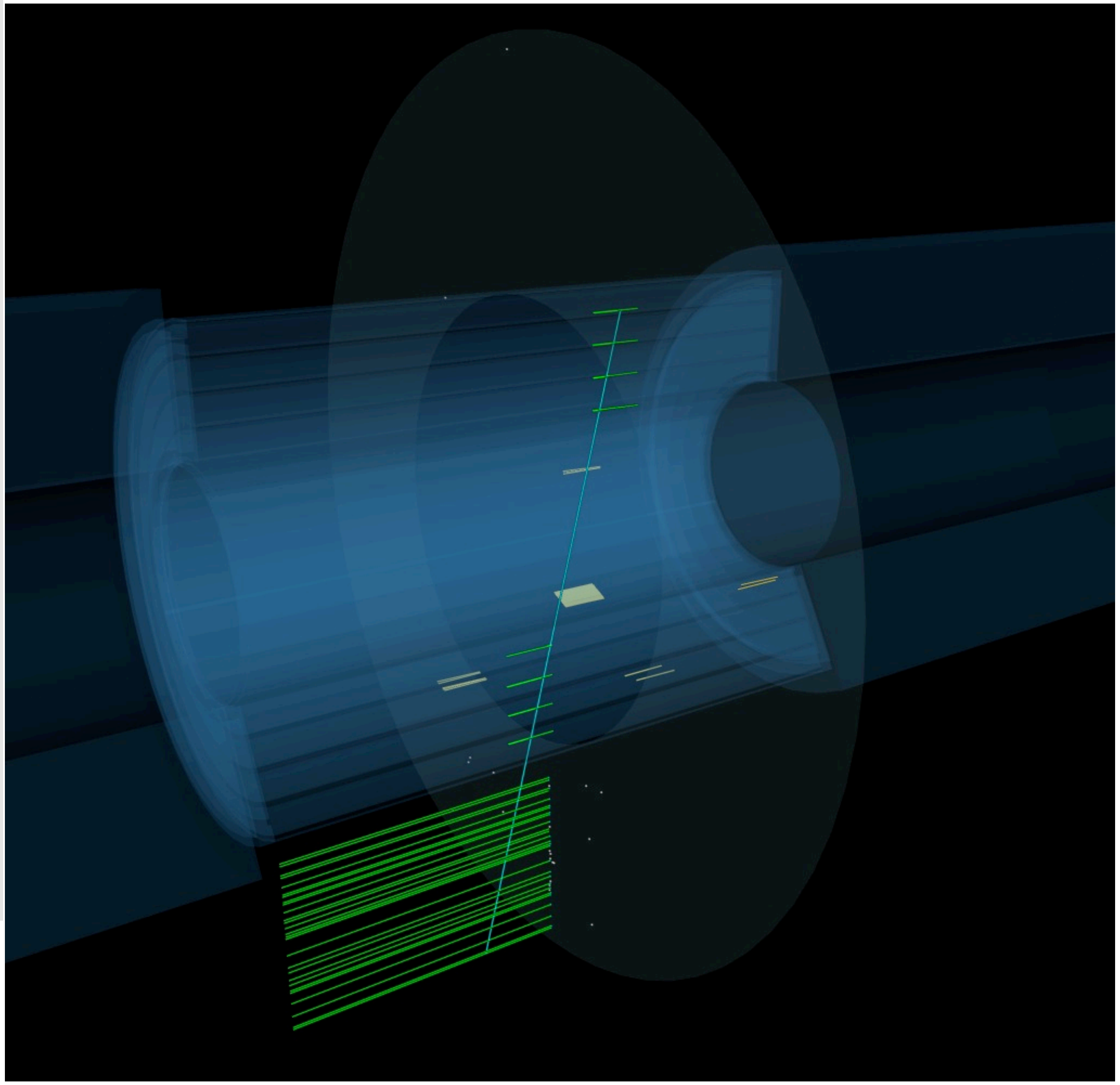




Track from cosmic ray event detected by SCT and TRT systems



- Major milestone in the detector commissioning: combination of DAQ, online and offline software.



SM at the LHC: what can be done with early data?

- Goals of SM physics studies with early data:
  - Use W, Z and top to calibrate the detector & triggers.
  - Control W, Z, top and QCD multi-jets to properly estimate the background for physics beyond the SM
  - Improve current SM measurements to provide stringent consistency tests of the underlying theory.

few pb^{-1}
$L \sim 10^{30}$ to 10^{31} cm^{-2} s^{-1}

several fb^{-1}
$L \sim 10^{32}$ to 10^{33} cm^{-2} s^{-1}

Process	σ(nb)	Ns^{-1}	$\mathcal{L}=10pb^{-1}$	$\mathcal{L}=10fb^{-1}$
Minimum bias	10^8	10^7	10^{12}	$\sim 10^{15}$
Inclusive jets – p_T>200GeV	100	100	10^6	$\sim 10^9$
$W \rightarrow e\nu$	15	15	10^5	$\sim 10^8$
$Z \rightarrow e^+e^-$	1.5	1.5	10^4	$\sim 10^7$
Dibosons	0.2	10^{-3}	10	10^4

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- [x] Extensive test beam characterization of prototypes and final modules. Also used for validation of G4 simulations.

- [ ] 'In situ' detector calibration:
  - [x] Cosmics runs;
  - [ ] Single beam and beam gas runs during LHC commissioning;
  - [ ] Calibration with physics processes;
    - – Procedure valid for all sub-detectors, ECAL, HCAL, inner trackers, Muon Chambers.

- [ ] Need to "re-discover the SM at the LHC before claiming any discovery of new physics!"

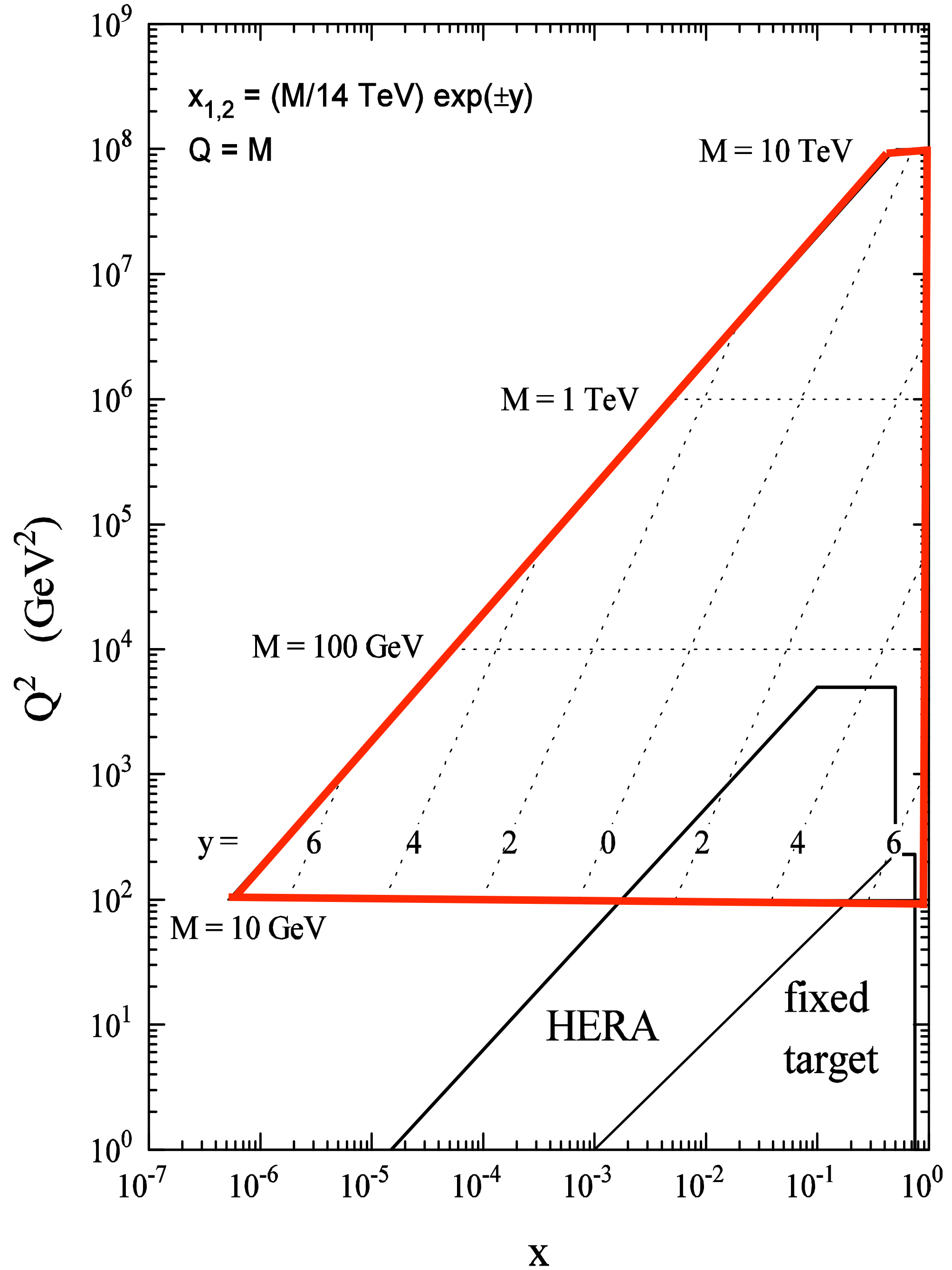
LHC Parton Kinematics

- Essentially all physics at LHC are connected to the interactions of quarks and gluons (small & large transferred momentum).

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just "rescaled" scattering at the Tevatron.
  - dominance of gluon on sea quark scattering;
  - large phase space for luon emission and thus for the production of extra jets;
  - intensive QCD background!

- **This requires a solid understanding of QCD.**

- The kinematic acceptance of the LHC detectors allows a large range of **x** and **Q²** to be probed (ATLAS coverage: |y| < 5).



pp collisions

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  - Hard processes (high-p_T): well described by perturbative QCD
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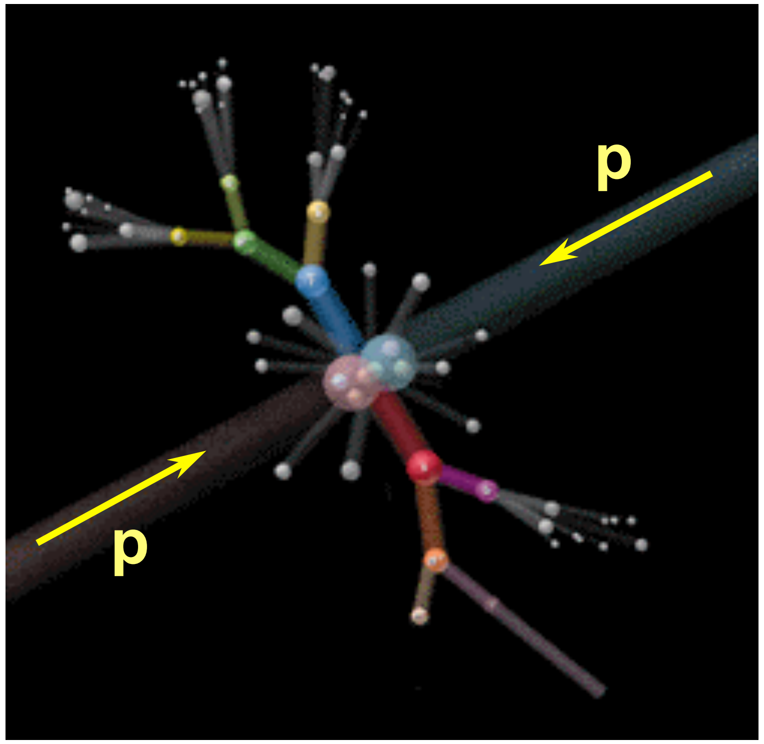

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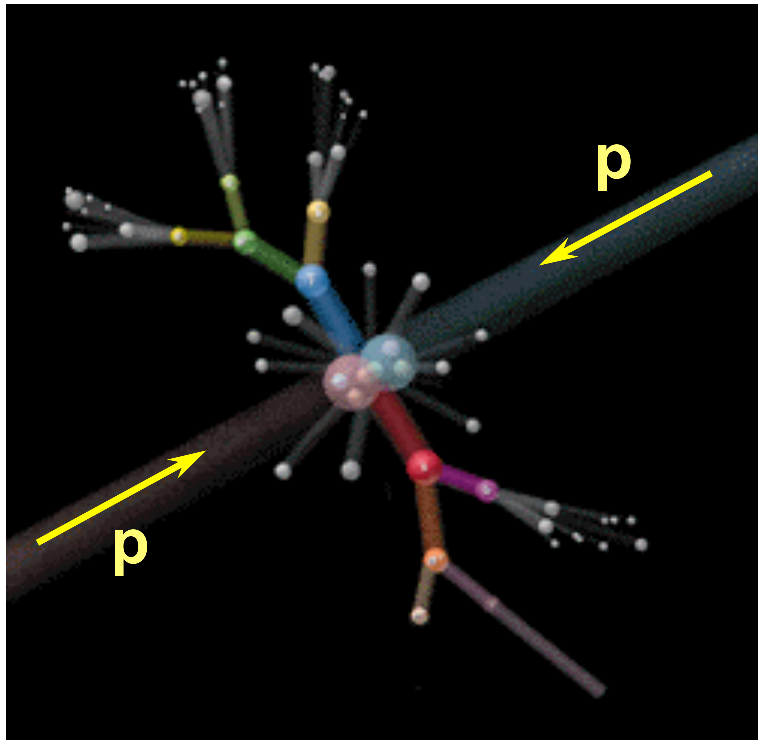
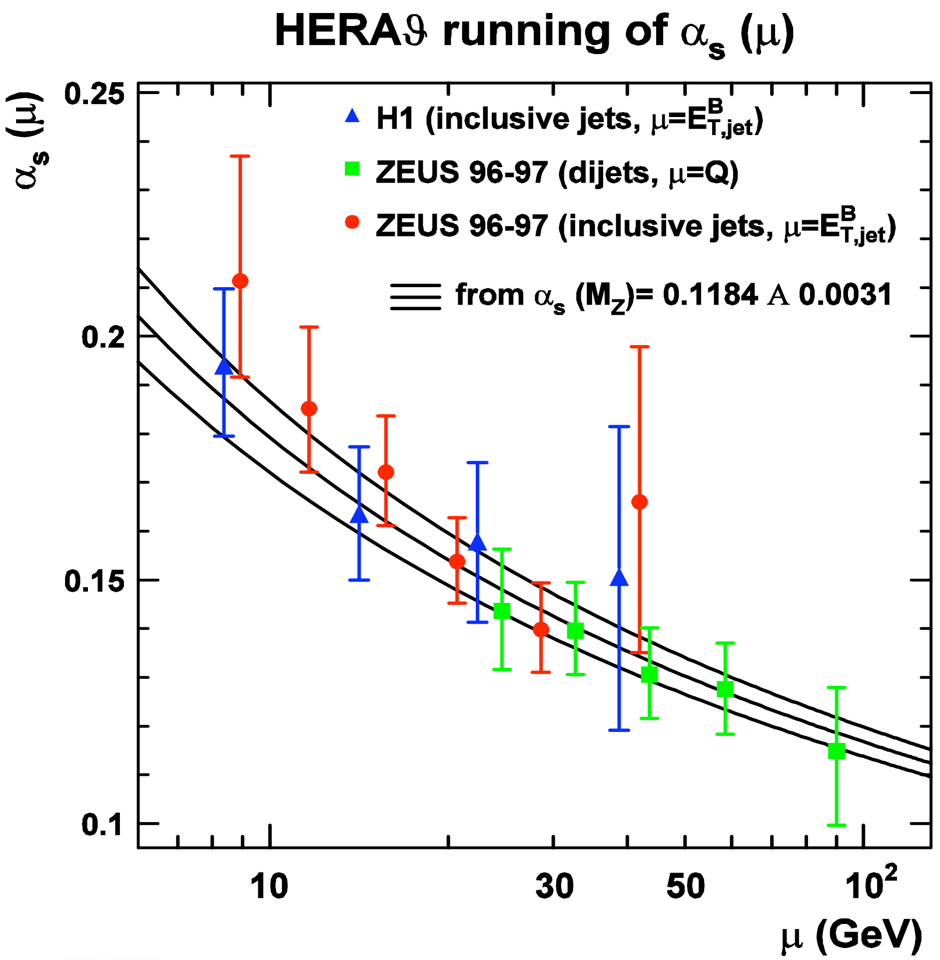




Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,…

- Minimum-bias events are dominated by "soft" partonic interactions.
- On average, minimum bias events have low transverse energy, low multiplicity.

Minimum bias measurements

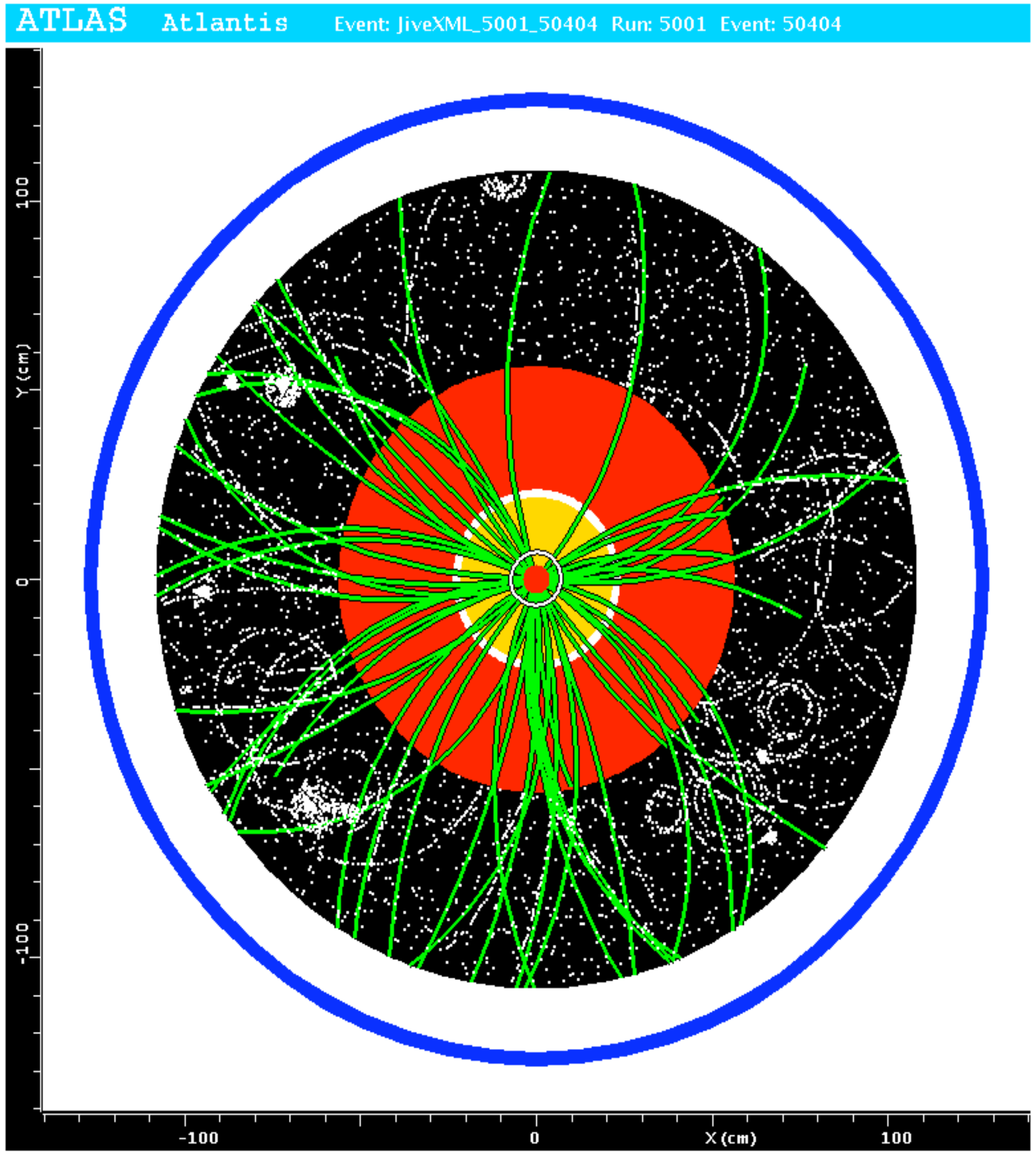
- **Experimental definition**: depends on the experiment's **trigger**!
- "Minimum bias" is usually associated to **non-single-diffractive events** (NSD), e.g. ISR, UA5, E735, CDF,…

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

$\sigma_{tot} \sim$ 102 - 118 mb (PYTHIA) (PHOJET)

minimum bias event

$\sigma_{NSD} \sim$ 65 - 73 mb (PYTHIA) (PHOJET)



- At the LHC, studies on minimum-bias **should be done early on**, at low luminosity to remove the effect of overlapping proton-proton collisions!

- Modeling of minimum bias pile-up and underlying event **necessary tool for high p_T physics!**

- Baseline measurement for heavy-ion studies.

- **Statistics of low p_T jets and minimum bias only limited by allocated trigger bandwidth.**

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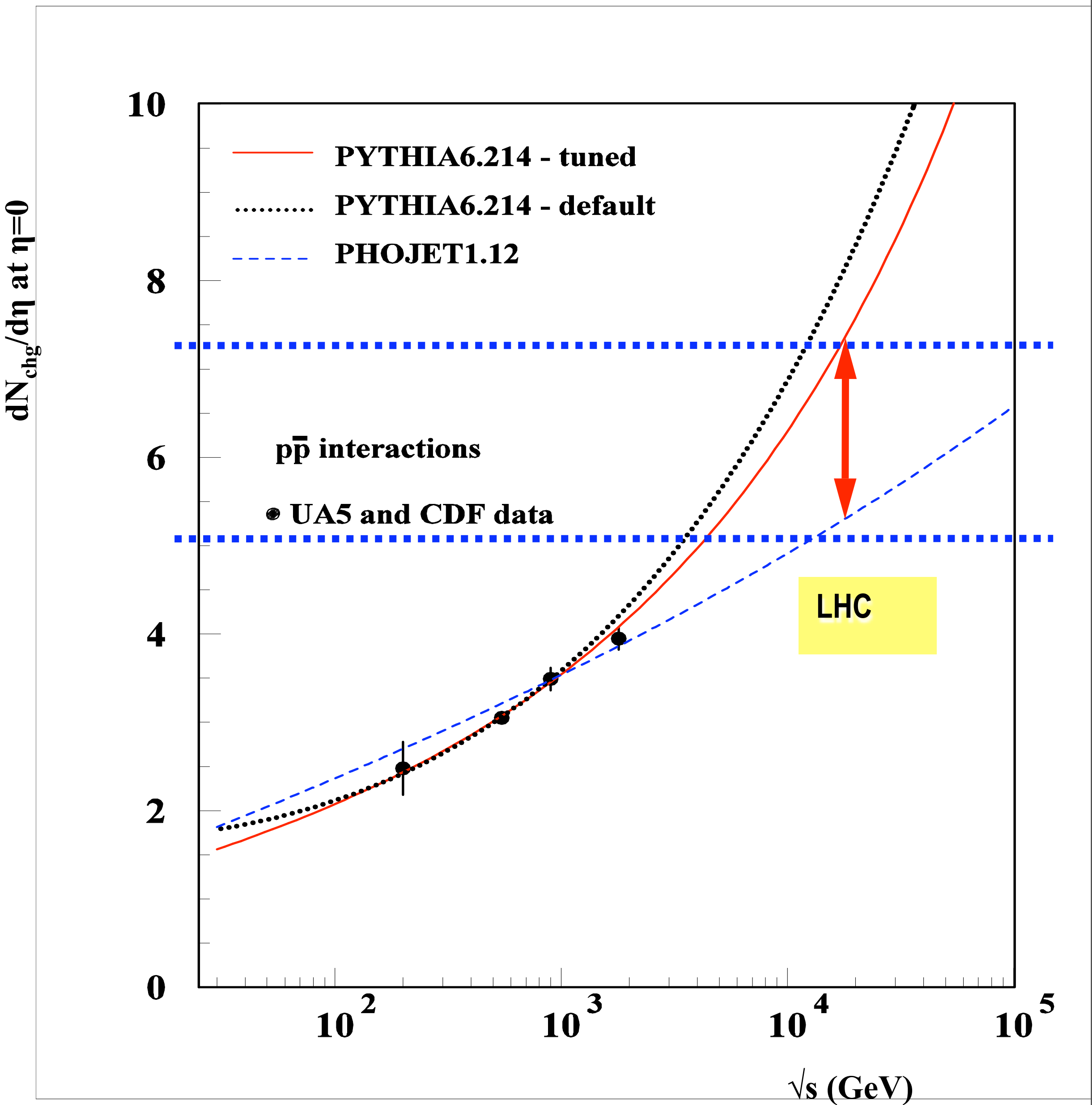

- **PYTHIA models favour $\ln^2(s)$;**
- **PHOJET suggests a $\ln(s)$ dependence.**

Triggering on minimum bias events

(strategy for low luminosity runs!)

What do we want in our final minimum bias sample?

- **most of the inelastic events** (with as little or "minimum" bias as possible).
- **later to be distilled into non-single diffractive inelastic events.**

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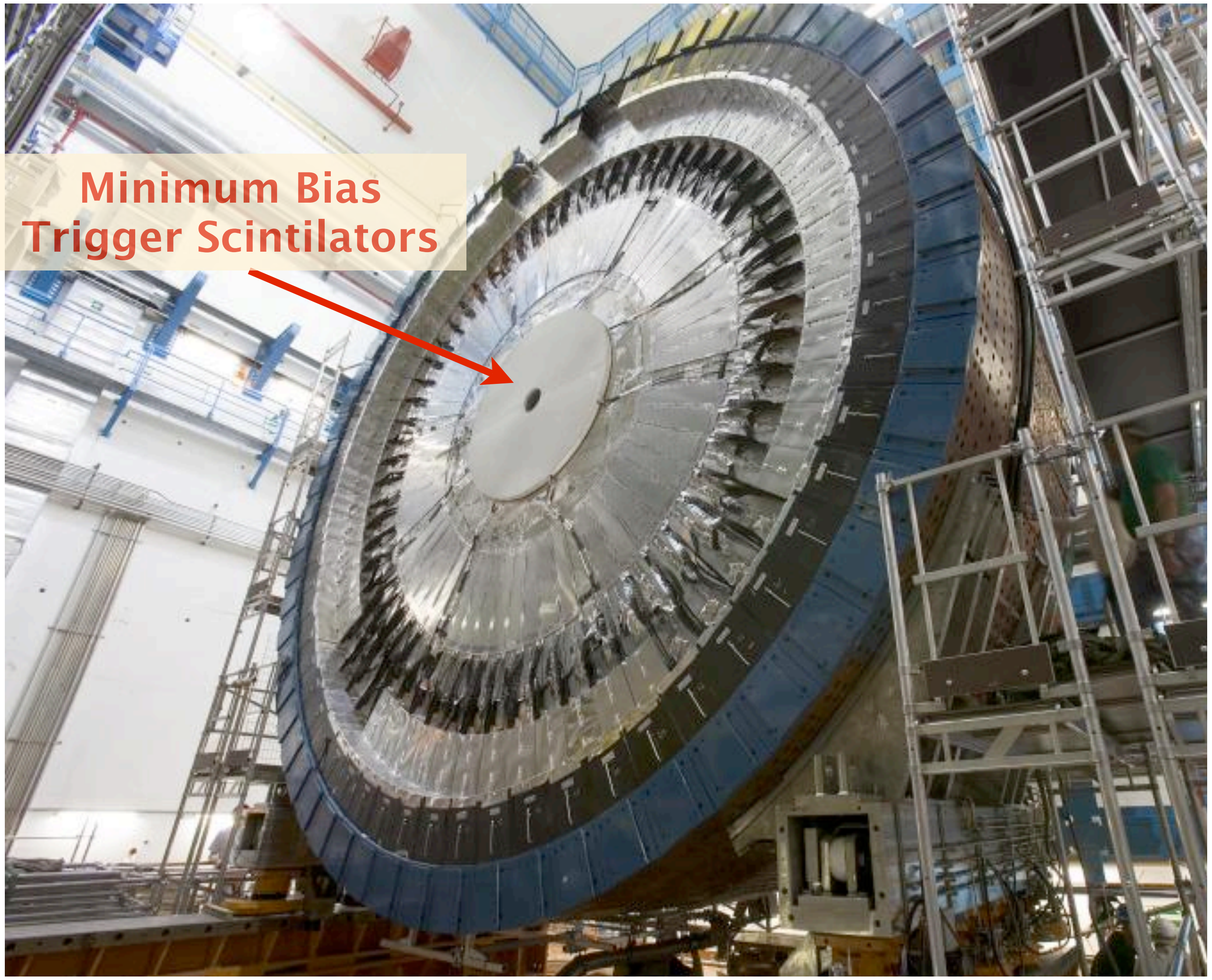
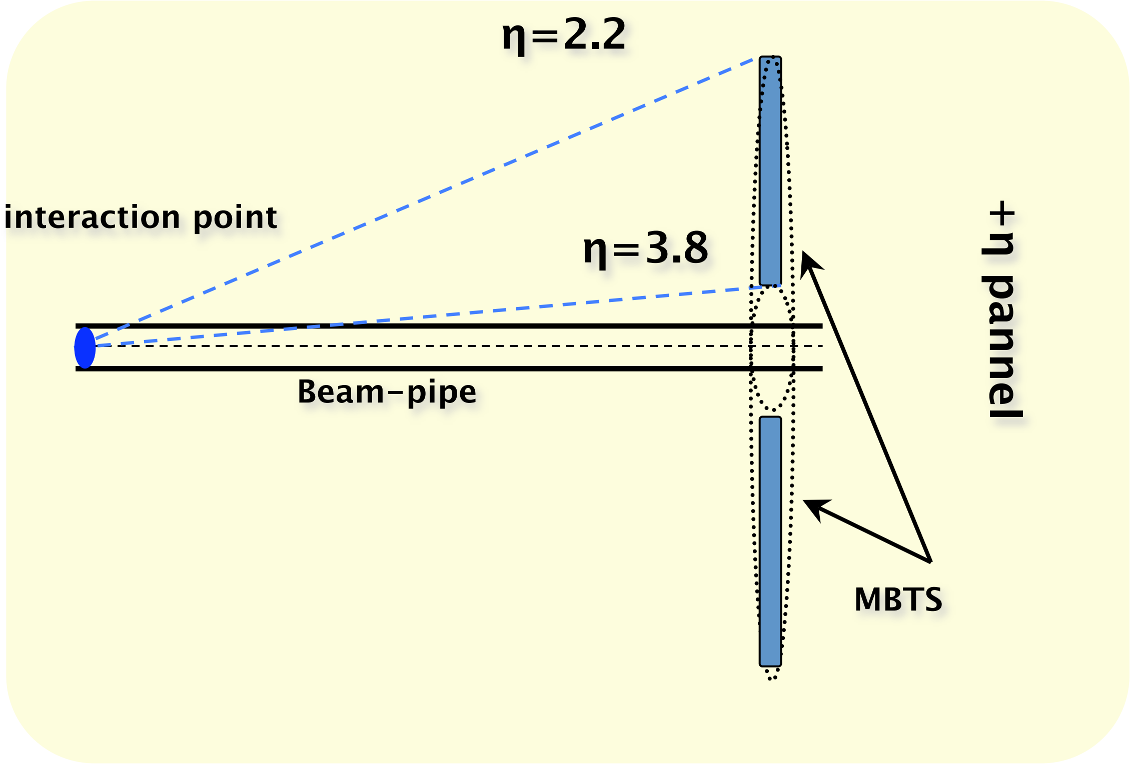
What do we need to separate?

- **Empty events** (for initial runs with bunch spacing of 75ns, most bunch crossings are expected to be empty at $L=10^{31}cm^{-2}s^{-1}$)**;**
- **Beam-gas;**
- **Beam-halo;**
- **Pile-up** (not so much of a big issue early on, but important for $L \sim 10^{33}cm^{-2}s^{-1}$ and greater).

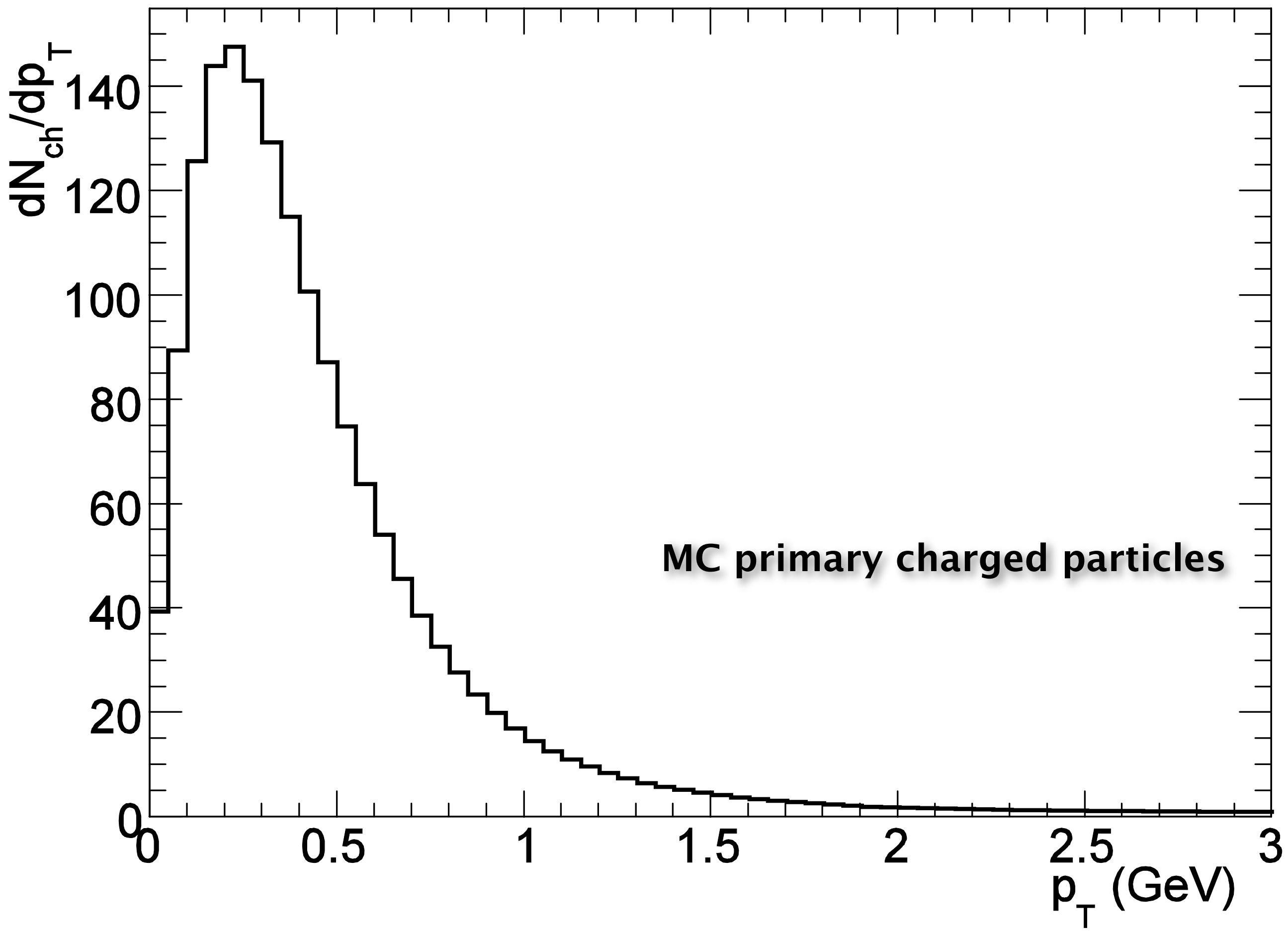
ATLAS trigger for minimum bias events (MBTS)





Reconstructing minimum bias events

- The goal is to reconstruct the event and recover all charged particles;
  - main limitation: soft track reconstruction!
  - standard reconstruction (default): low p_T cut set to 500MeV;



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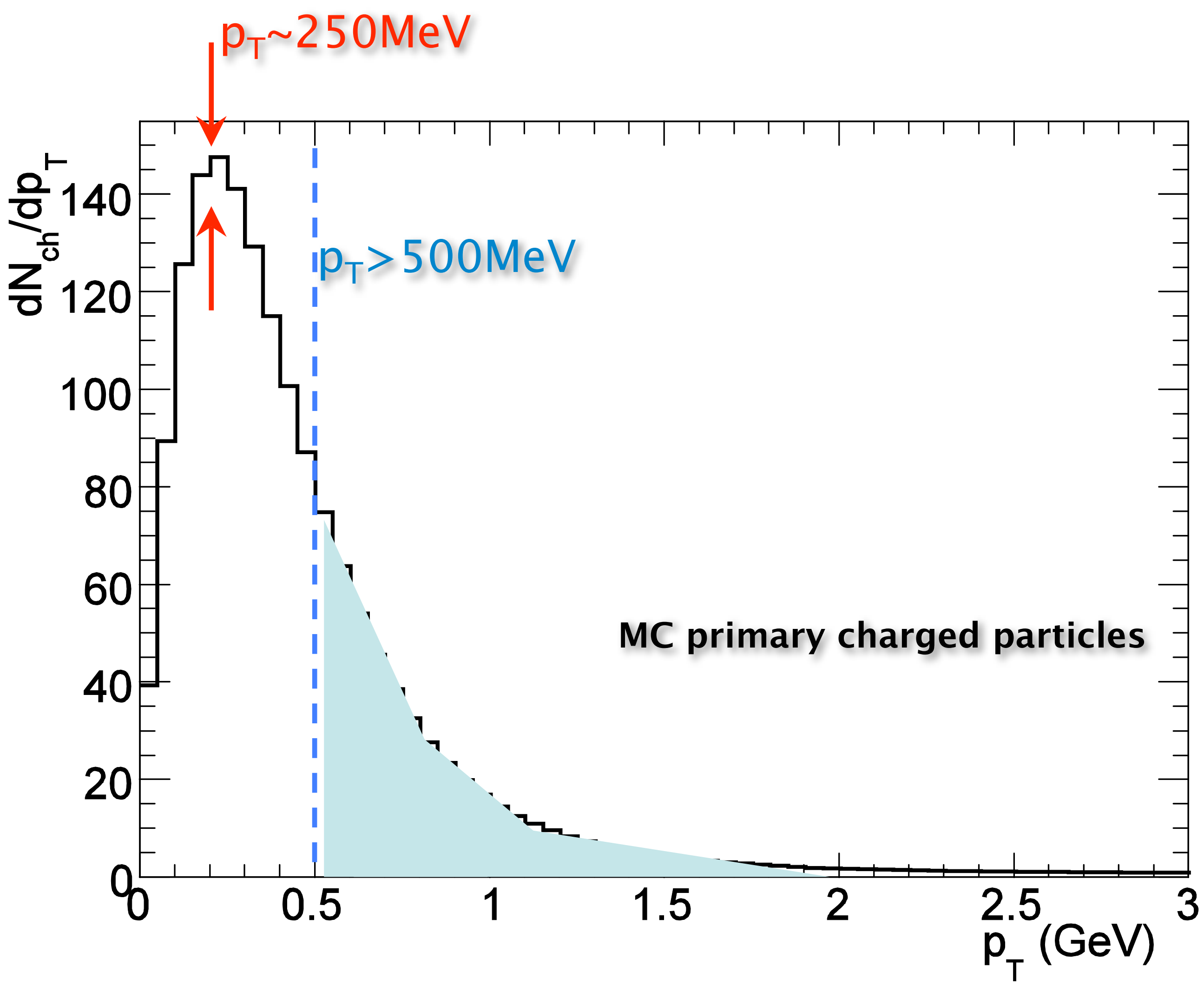
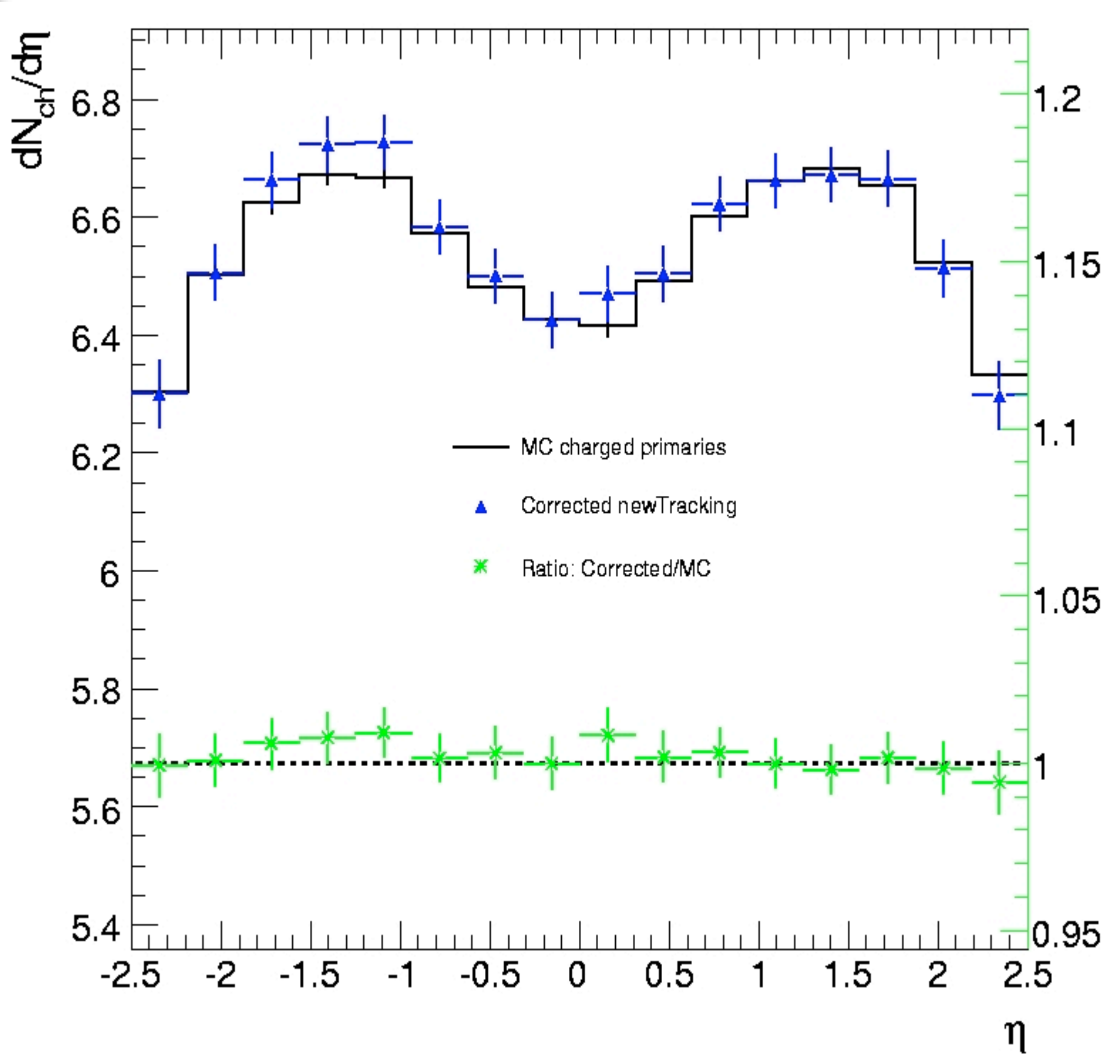


- Work is being done to push this limit to p_T ~ 100 – 200 MeV;
- Avoid large extrapolation factors for measurements such as $dN_{ch}/d\eta$.

Reconstructing minimum bias events

MC charged primaries & track p_T > 150MeV

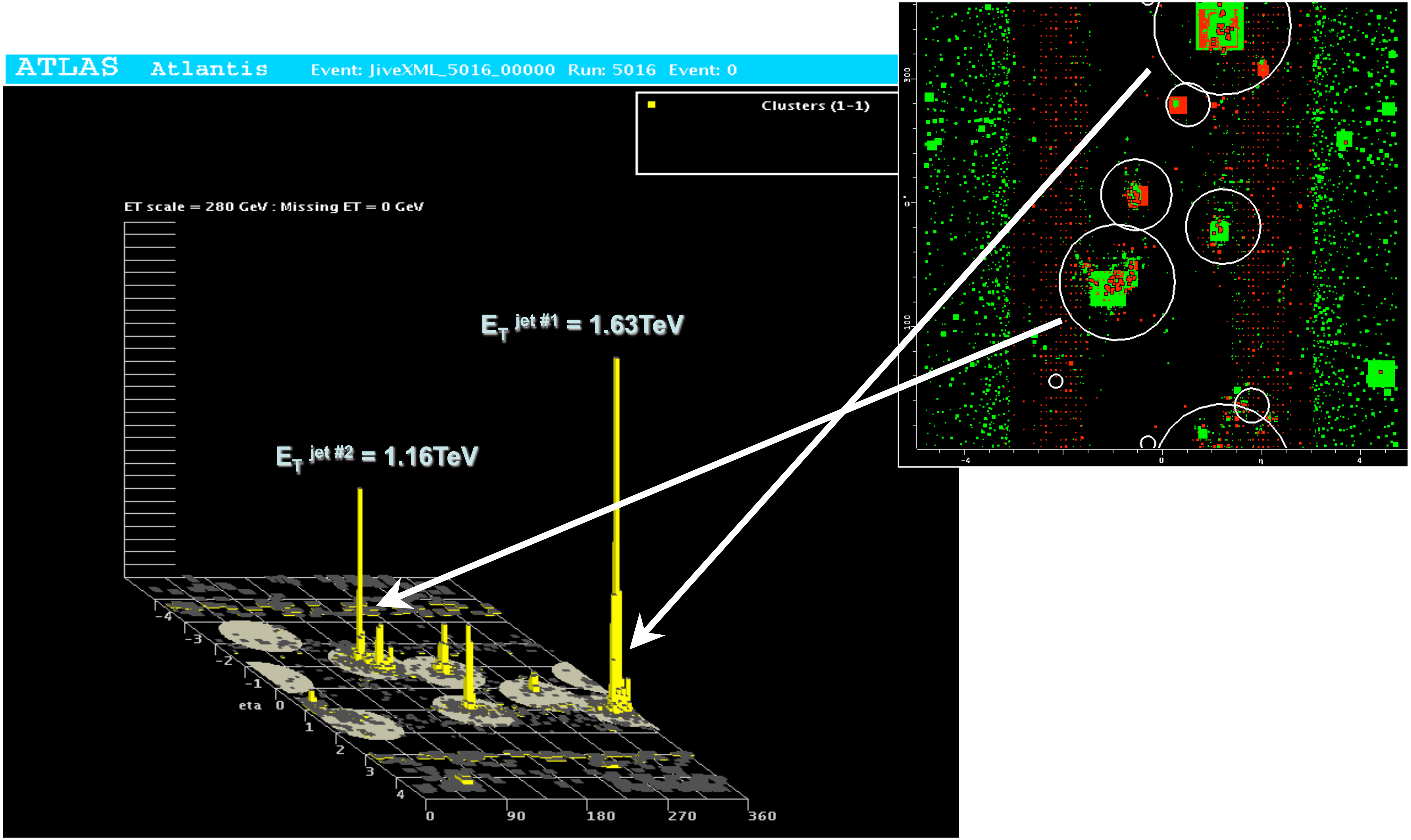


Summary of systematic uncertainties

Track selection cuts	2%
Mis-estimate of secondaries	1.5%
Vertex reconstruction	0.1%
Mis-alignment	6%
Beam-gas & pile-up	1%
Particle composition	2%
Diffractive cross-sections	0.1%
Total:	**6.9%**

Corrections:
- Track-to-particle correction
- Vertex reconstruction correction
- Trigger bias

Measuring Jets with ATLAS



(Simulated event!)

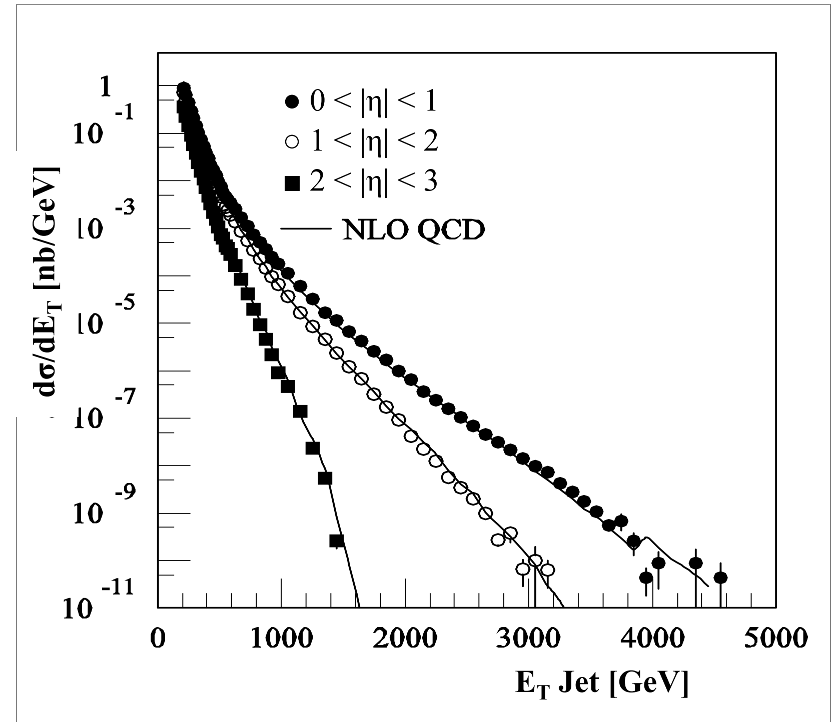
Jet physics

L = 30 fb^{-1}

Jet E_T	N_{events}
> 1 TeV	4 x 10^5
> 2 TeV	3 x 10^3
> 3 TeV	40

- Test of pQCD in an energy regime never probed!
- The measurement of di-jets and their properties (E_T and $\eta_{1,2}$) can be used to **constrain p.d.f.'s**.
- Inclusive jet cross section: **$\alpha_S(M_Z)$** measurement with **10% accuracy.**

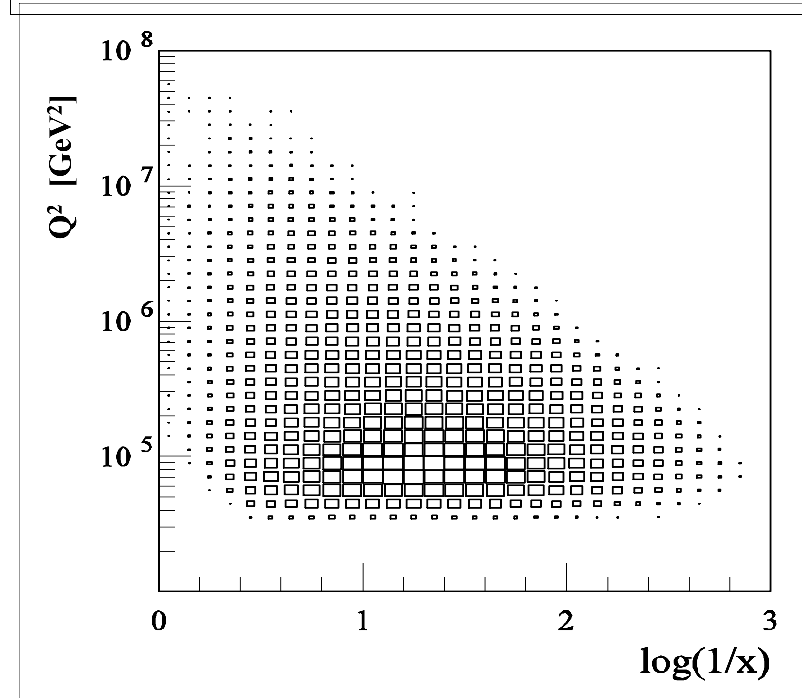
(can be reduced by using the 3-jet to 2-jet production)



- Multi-jet production is important for several physics studies:
  - a) $t\bar{t}$ production with hadronic final states
  - b) Higgs production in association with tt and $b\bar{b}$
  - c) Search for R-parity violating SUSY (8 – 12 jets).

– **Systematic uncertainties**:

- jet algorithm,
- calorimeter response (jet energy scale),
- jet trigger efficiency,
- luminosity (dominant uncertainty 5% –10%),
- the underlying event.



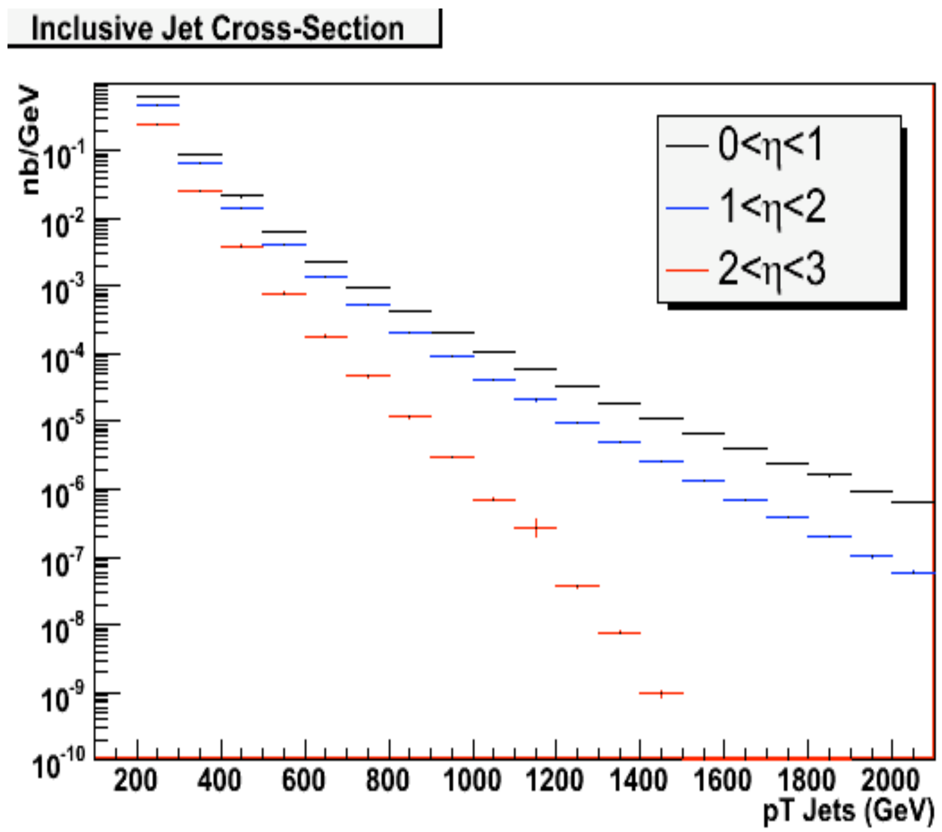
At the LHC the statistical uncertainties on the jet cross-section will be small.

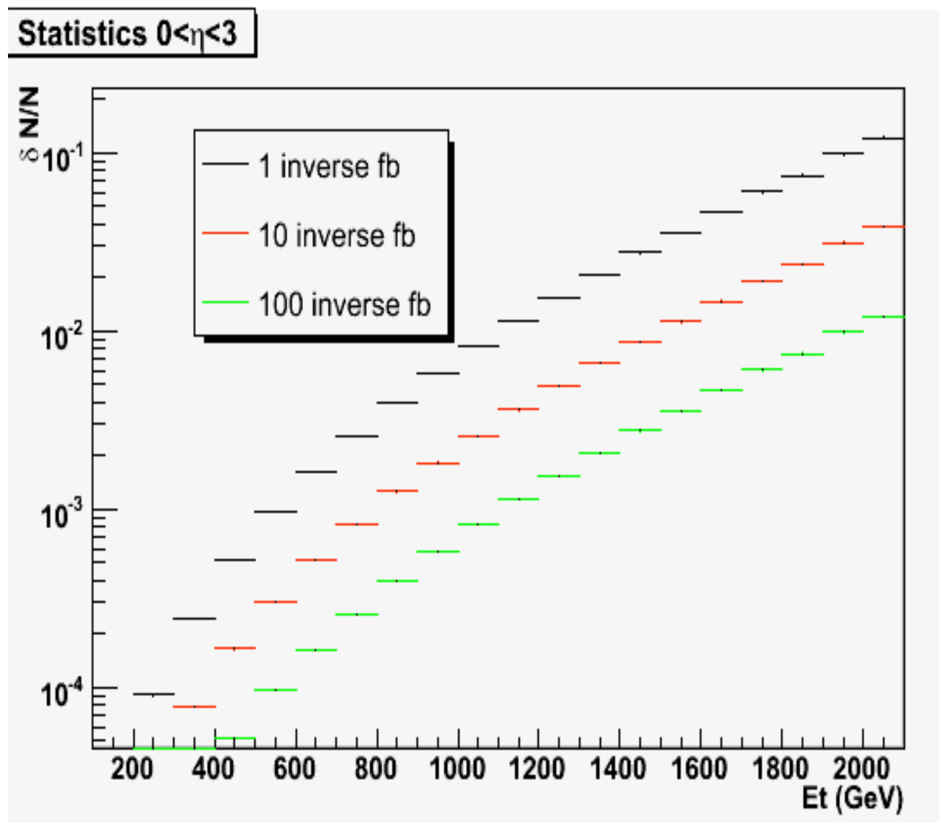
Inclusive jet cross-section

- Inclusive jet cross-section measurement:
  - test QCD;
  - measure PDFs;
  - measurement can also be used to look for new physics (e.g. quark compositeness).

- Statistical uncertainties are negligible! New studies are using trigger aware analysis to re-estimate uncertainties (pre-scales need to be included)!

- Systematic uncertainties are expected to dominate!
  - Jet energy scale uncertainty will be the big challenge.
  - Target is to get JES down to ~1%, not an easy task!

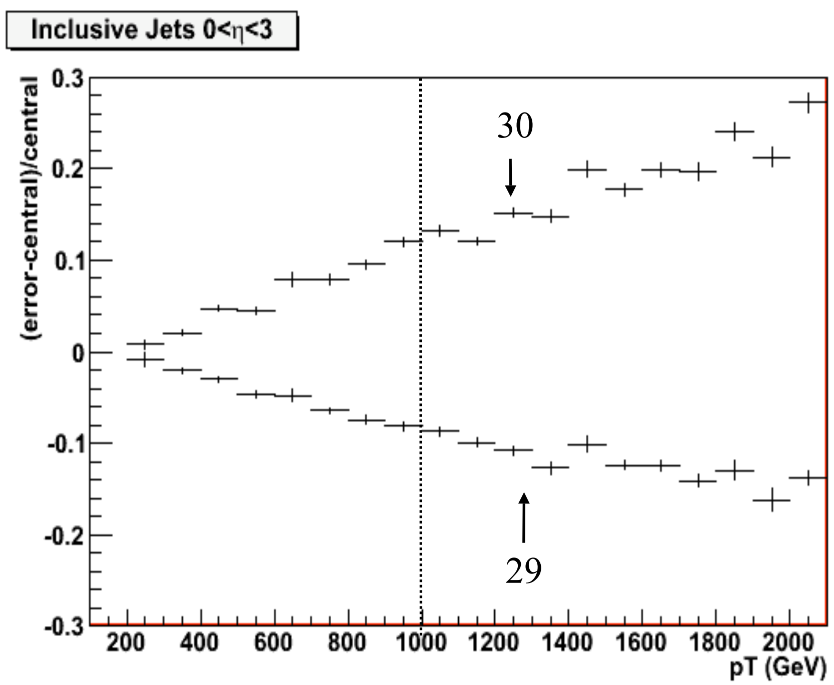




Constraining PDFs with early jet measurements

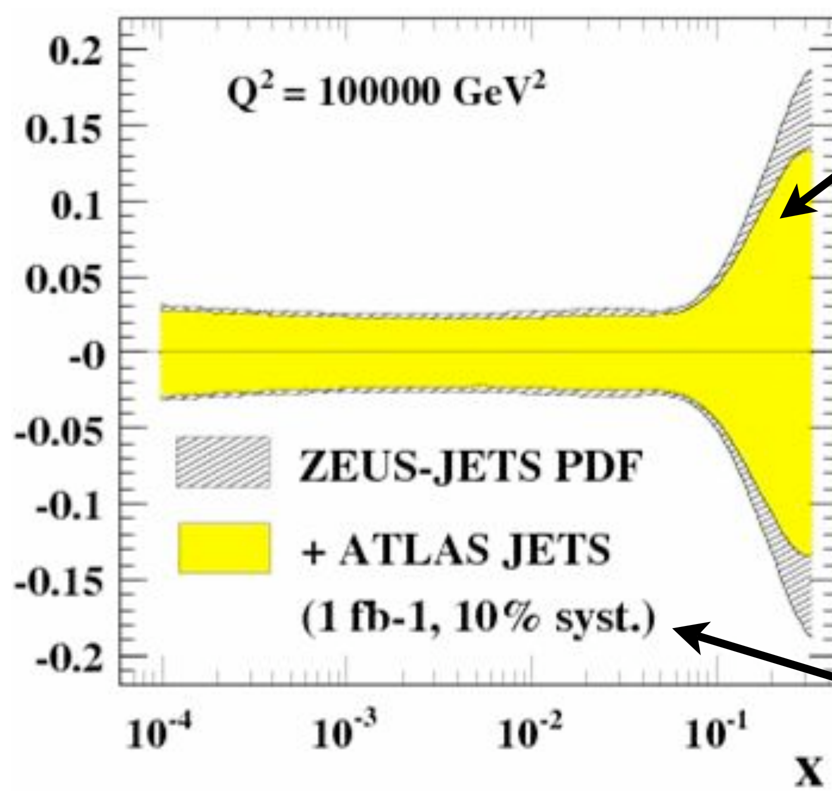
PDF fitting using pseudo-data

- Plotted the relative change in the inclusive jet cross-section as calculated with error PDFs w.r.t to best fit:



- **For a jet p_T of 1TeV the PDF uncertainties are approximately 10% to 15%.**

- Grids were generated for the inclusive jet cross-section at ATLAS in the pseudorapidity ranges $0<\eta<1$, $1<\eta<2$, and $2<\eta<3$ up to p_T=3TeV (NLOJET).
- In addition pseudo-data for the same process was generated using JETRAD.
- The pseudo-data was then used in a global (ZEUS) fit to assess the impact of ATLAS data on constraining PDFs:



Preliminary indications suggest that ATLAS data can constrain the high x-gluon.

Systematic uncertainties are uncorrelated, $10fb^{-1}$=1 year of nominal data-taking

Di-jet azimuthal decorrelation

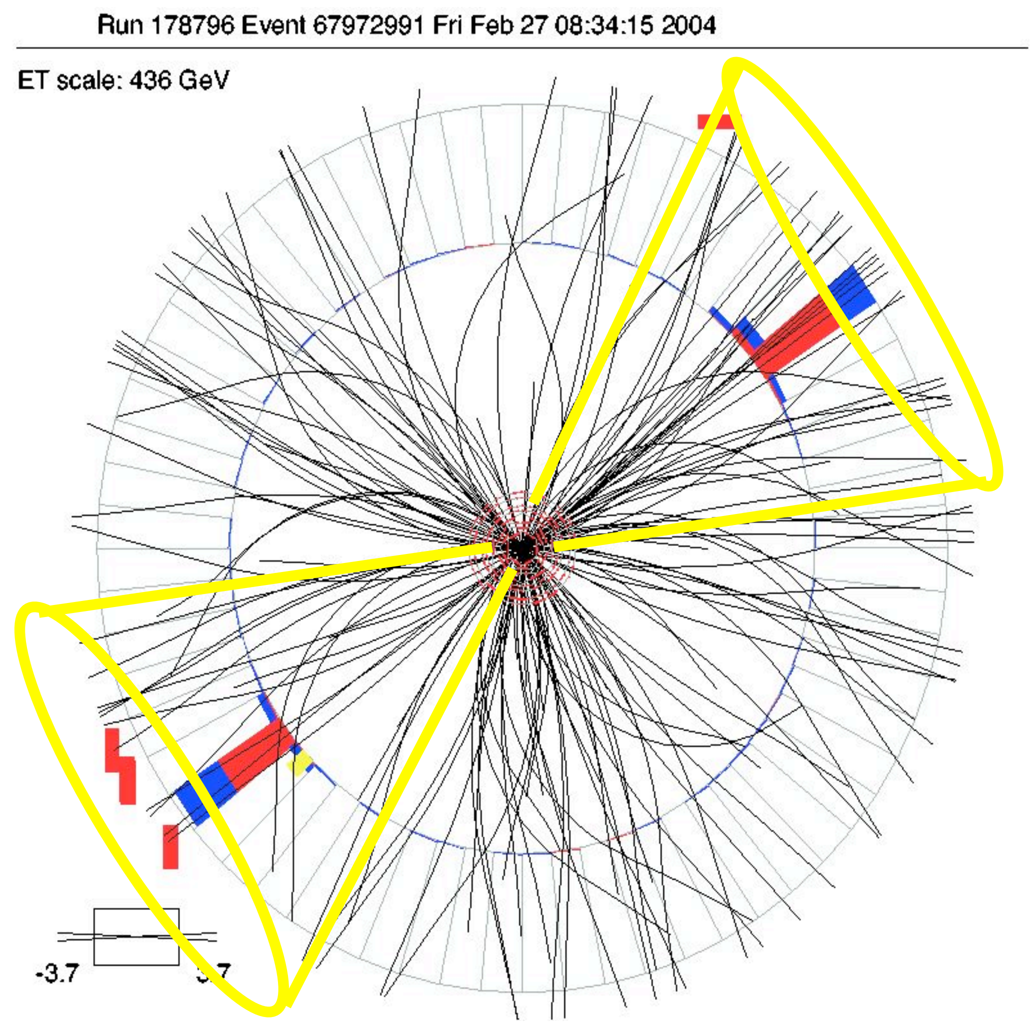
Dijet production in hadron-hadron collisions result in $\Delta\varphi_{dijet} = | \varphi_{jet1} - \varphi_{jet2} | = \pi$ in the absence of radiative effects.

$\Delta\varphi_{dijet} = \pi$ → 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-p_T jet

small $\Delta\varphi_{dijet}$ - no limit → multiple additional hard jets in the event



hep-ex/0409040 Sep. 2004
PRL **94**, 221801 (2005)

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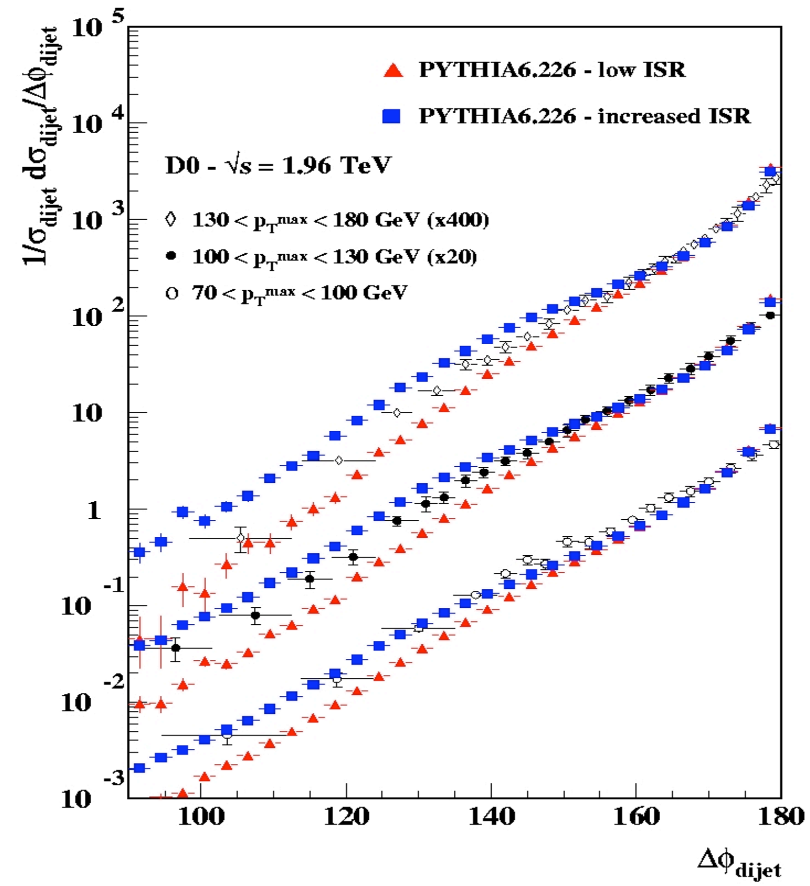
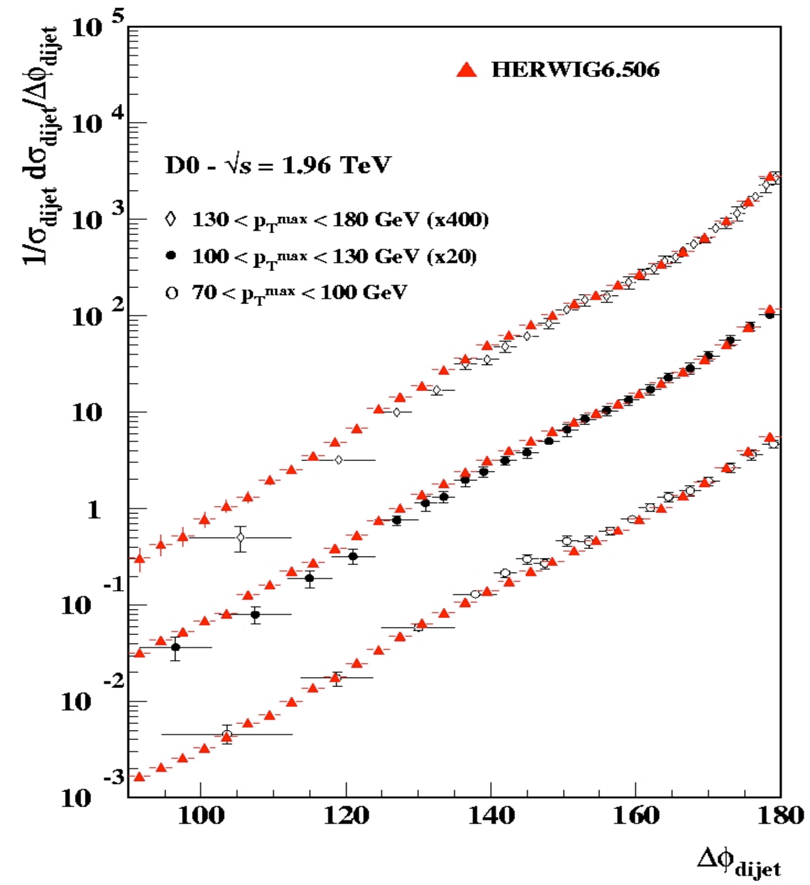
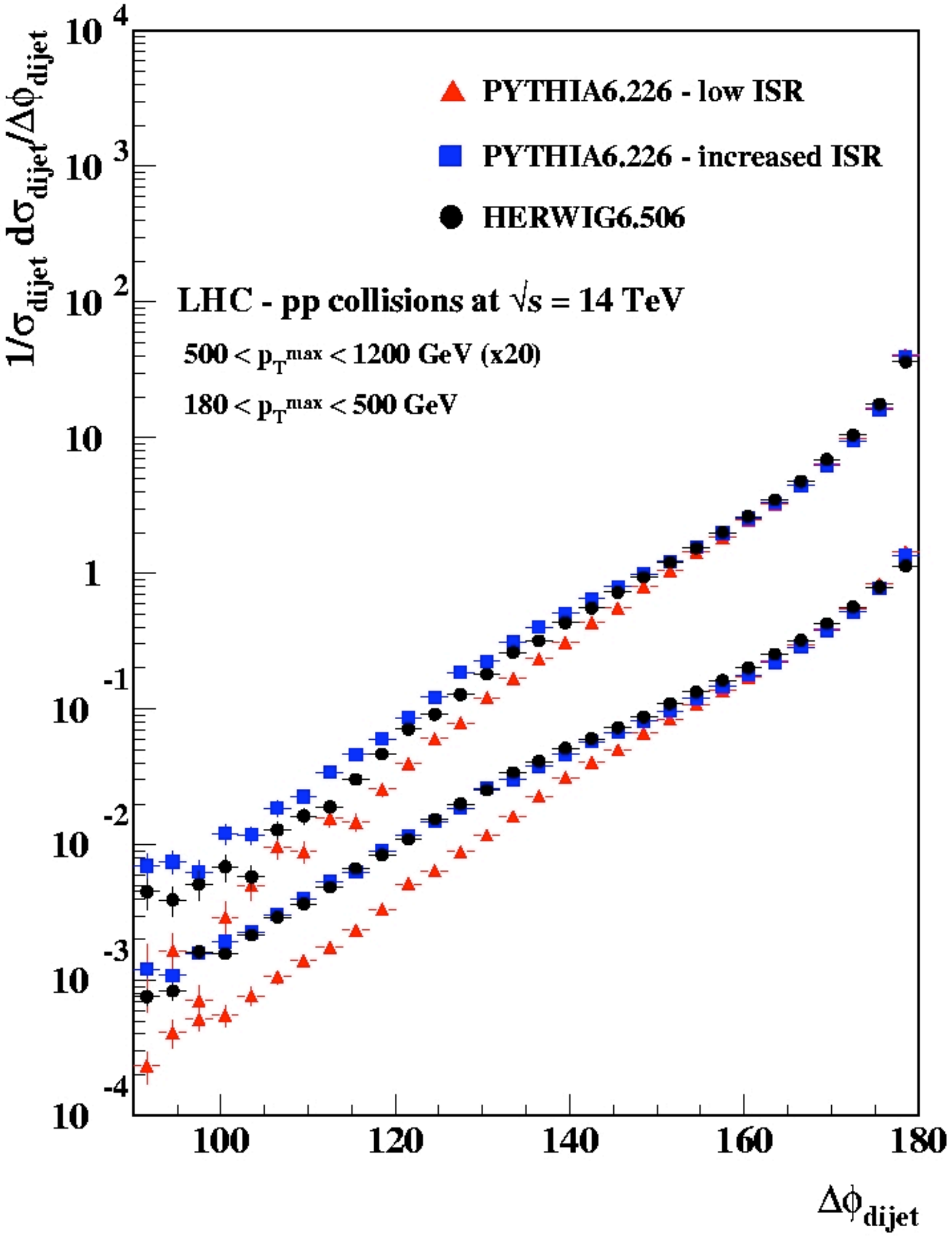




Azimuthal di-jet decorrelation with reconstructed jets

- Early measurement to benchmark generators particularly parton showers/higher orders.
- Work to do:
  - repeat with Sherpa and new PYTHIA PS model,
  - repeat with larger sample of simulated / reconstructed data



ATL-PHYS-PUB-2006-013

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Integrated luminosity / Number of events		
	This study:	~end of 2008
J5	1.6 pb^{-1} / 20K	0.5 fb^{-1} / 6.25 x 10^6
J6	56 pb^{-1} / 20K	0.5 fb^{-1} / 1.8 x 10^5

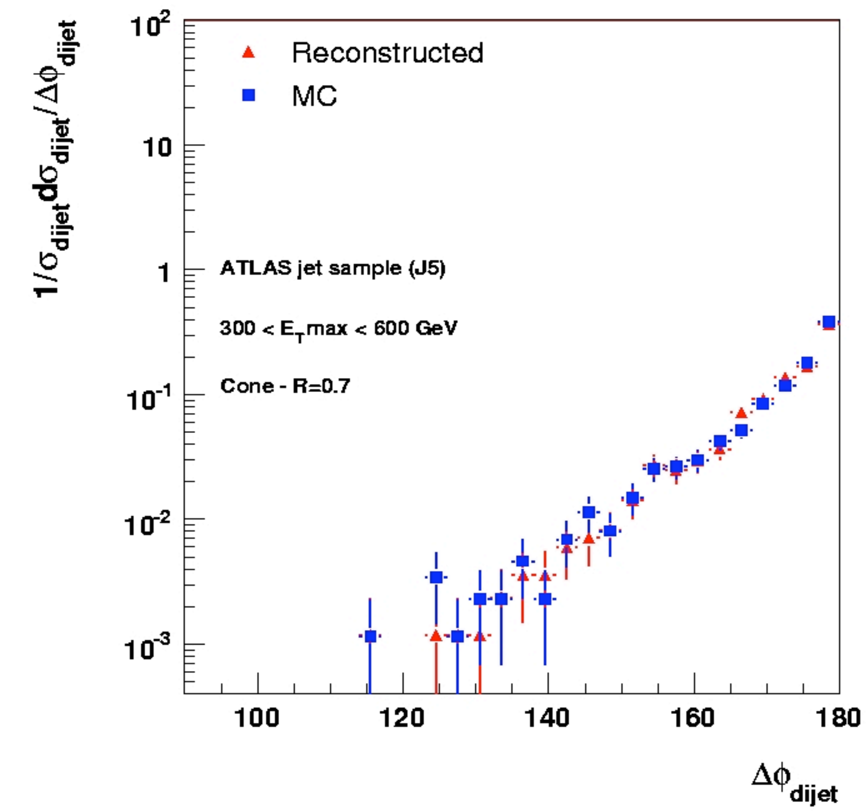
Selecting di-jet events:

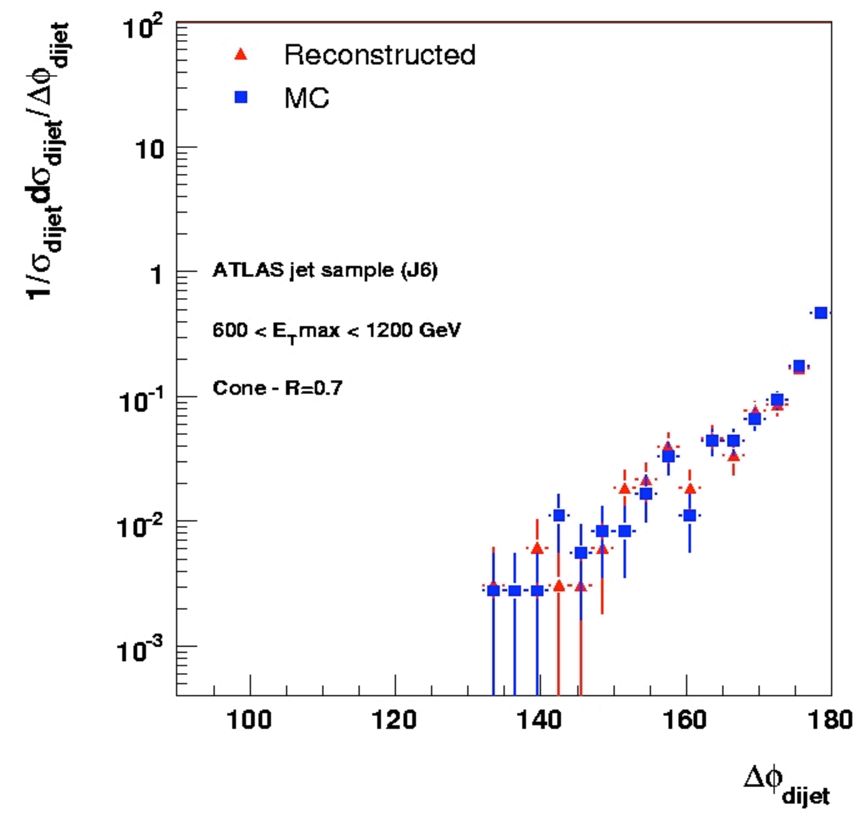
Cone jet algorithm (R=0.7)
N_{jets} = 2,
$|\eta_{jet}| < 0.5$,
$E_T^{jet\,\#2} > 80$ GeV,

Two analysis regions:

$300 < E_T^{MAX} < 600$ GeV → J5

$600 < E_T^{MAX} < 1200$ GeV → J6





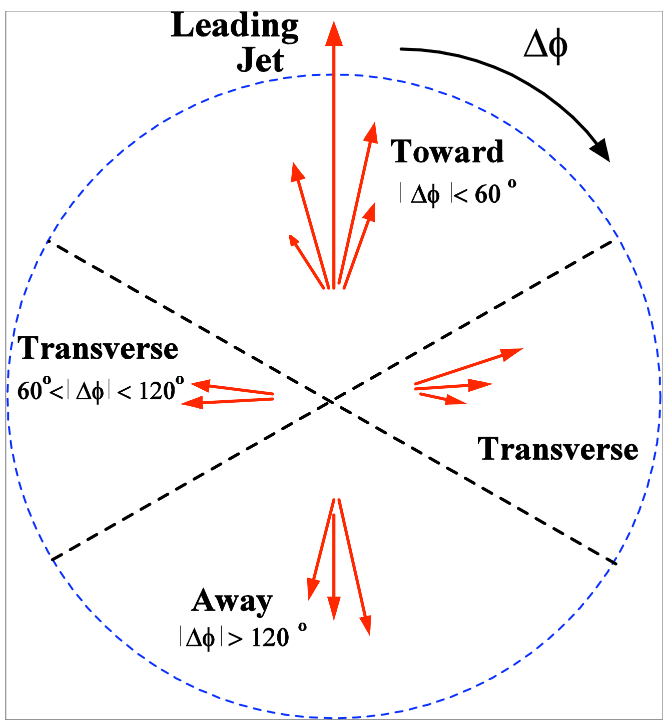
ATL-PHYS-PUB-2006-013

The underlying event in pp collisions at $\sqrt{s}$ = 14 TeV

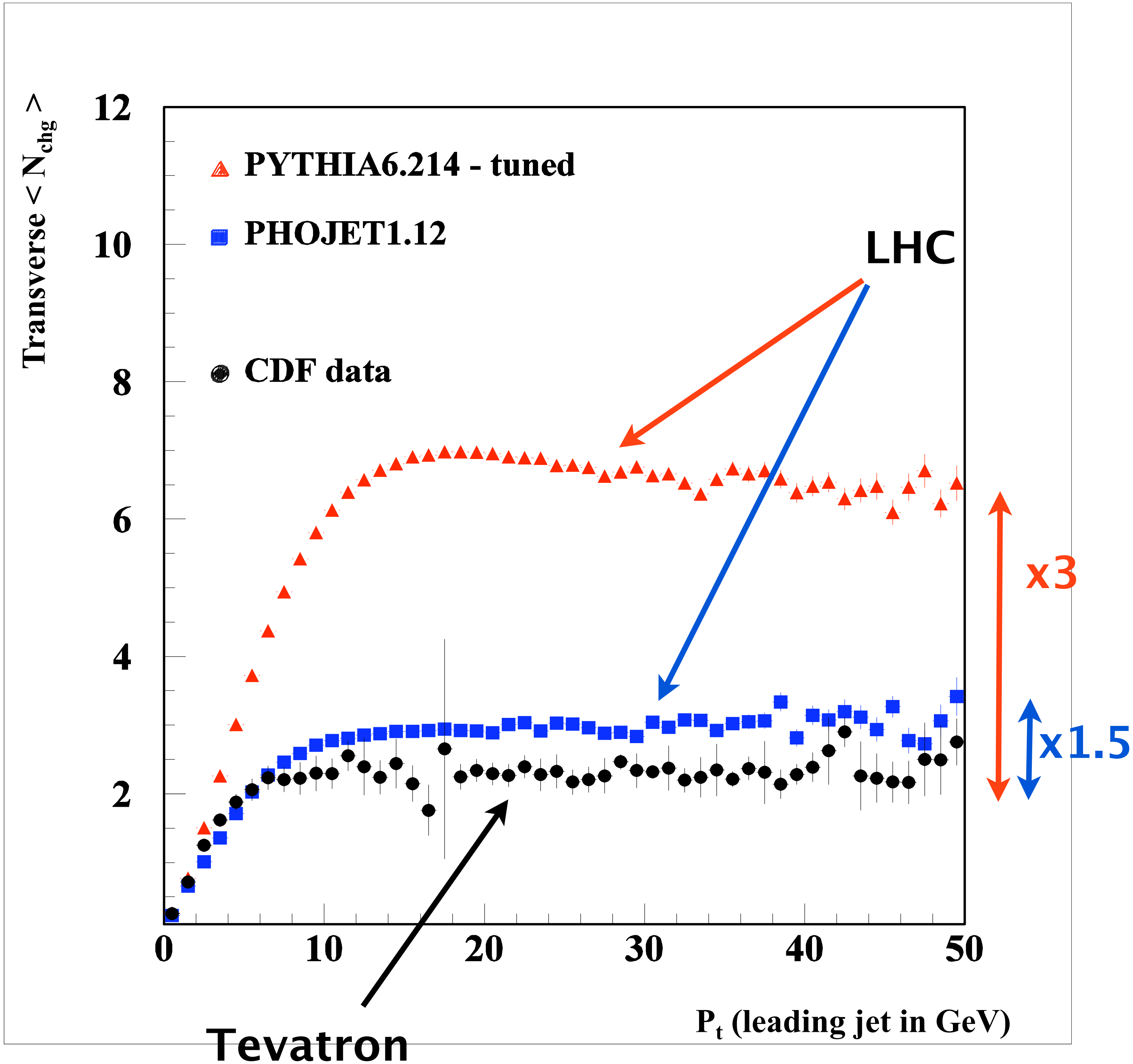
CDF - Run I "Style"

Charged particles:
p_t>0.5 GeV and |η|<1

Cone jet finder: R=0.7



UE particles come from region transverse to the leading jet.



Reconstructing the underlying event

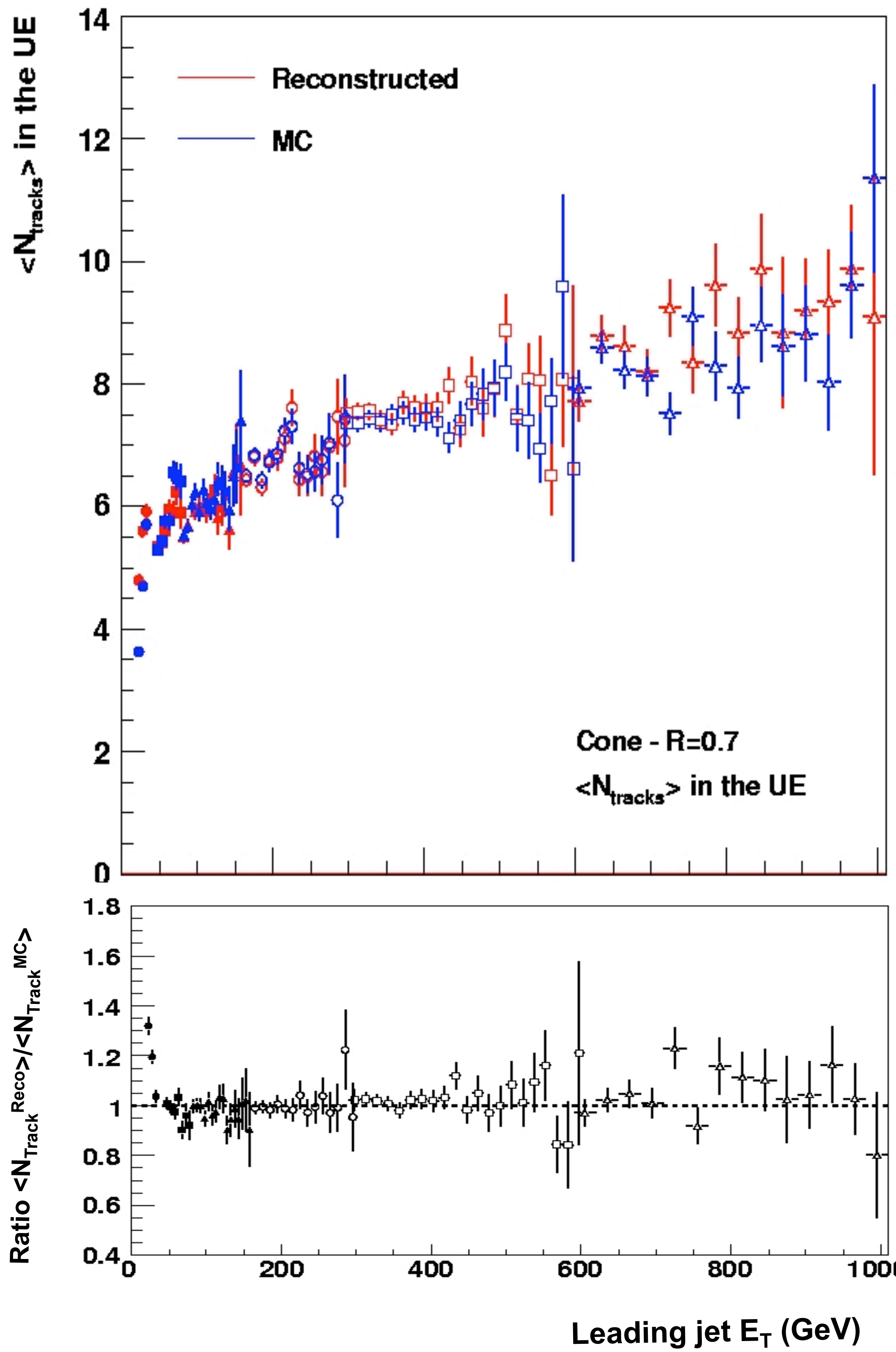
Selecting the underlying event:

i. Jet events:

$N_{jets} > 1$,
$|\eta_{jet}| < 2.5$,
$E_T^{jet} > 10$ GeV,

ii. Tracks:

$|\eta_{track}| < 2.5$,
$p_T^{track} > 1.0$ GeV/c



- Jet measurements with early data at ATLAS will extend considerably our knowledge of the underlying event!

- This study used ~ 60 pb^{-1} of integrated luminosity (few days at $L=10^{32}cm^{-2}s^{-1}$, $\varepsilon=50\%$)!

Measuring parton luminosities and p.d.f.'s

$$N_{events}\ (pp \to X) = L_{pp} \times pdf(x_1,x_2,Q^2) \times \sigma_{theory}(q,q,g \to X)$$

Uncertainties in **p-p luminosity (±5%)** and **p.d.f.'s (±5%)** will limit measurement uncertainties to ±5% (at best).

- For **high Q^2** processes LHC should be considered as a **parton-parton collider** instead of a p-p collider.
- Using only **relative cross section measurements, might lead eventually to accuracies of ±1%**.

$\bar{q}q$ (u,d) (high-mass DY lepton pairs and other processes dominated by $\bar{q}q$)	**W± and Z** leptonic decays	▪ precise measurements of mass and couplings; ▪ huge cross-sections (~nb); ▪ small background. ▪ x-range: 0.0003 - 0.1 ▪ ± 1%
g (high-Q^2 reactions involving gluons)	**γ-jet**, Z-jet, W±-jet	▪ γ-jet studies: γ p_T > 40 GeV ▪ x-range: 0.0005 - 0.2 ▪ γ-jet events: γ p_T ~ 10-20 GeV ▪ low-x: ~ 0.0001 ▪ ±1%
s, c, b	**γc, γb, sg→Wc**	▪ quark flavour tagged γ-jet final states; ▪ use inclusive high-p_T μ and b-jet identification (lifetime tagging) for c and b; ▪ use μ to tag c-jets; ▪ 5-10% uncertainty for x-range: 0.0005 - 0.2

Direct photon production

Understanding photon production:

- Higgs signals **($H \to \gamma\gamma$)** & background;
- prompt-photon can be used to study the underlying parton dynamics;
- gluon density in the proton, **$f_g(x)$** (requires good knowledge of α_s)

Production mechanism:

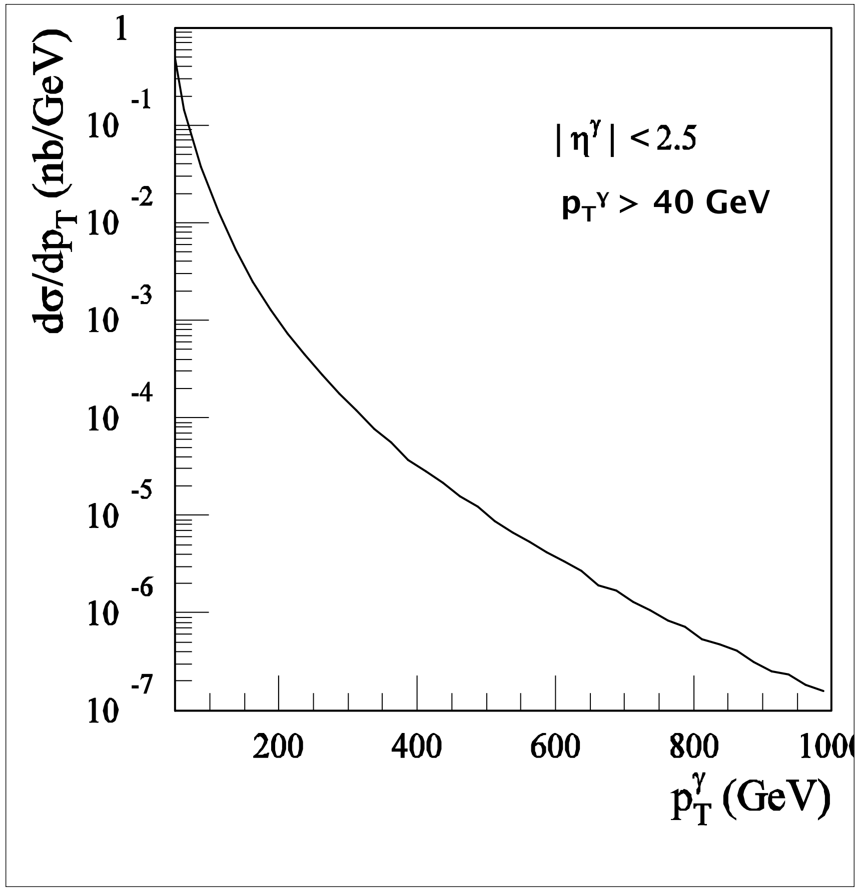
$qg \to \gamma q$	dominant (QCD Compton scattering)
$q\bar{q} \to \gamma g$	

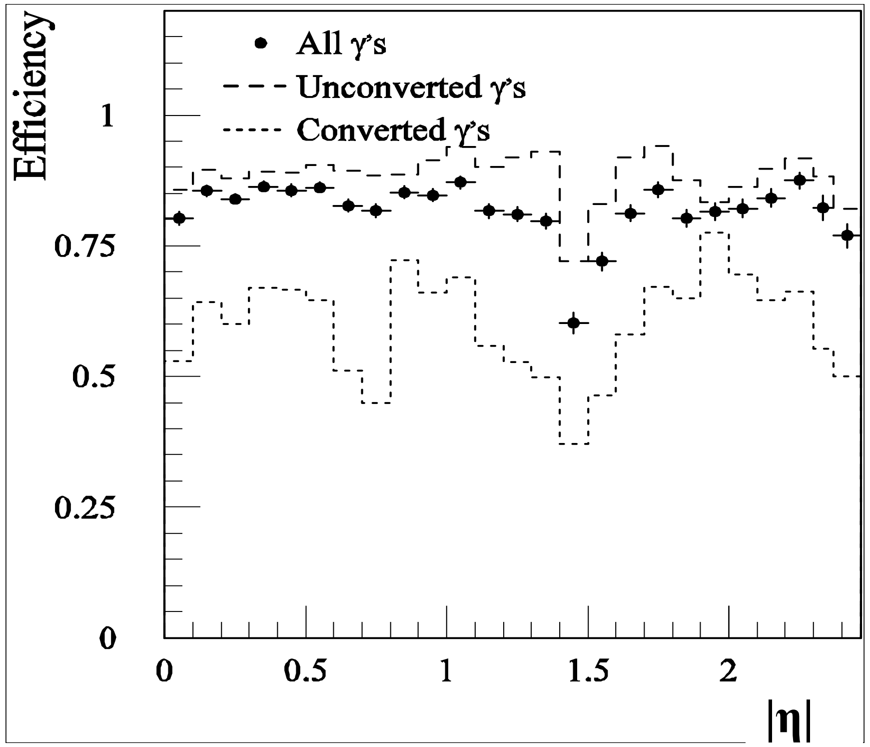
Background: mainly related to fragmentation
(non-perturbative QCD)

Isolation cut: reduces background from fragmentation (π^0)
(cone isolation)

ATLAS: high granularity calorimeters ($|\eta| < 3.2$) allow good background rejection.

Low luminosity run: the photon efficiency is more than **80%** (LAr calorimeter).





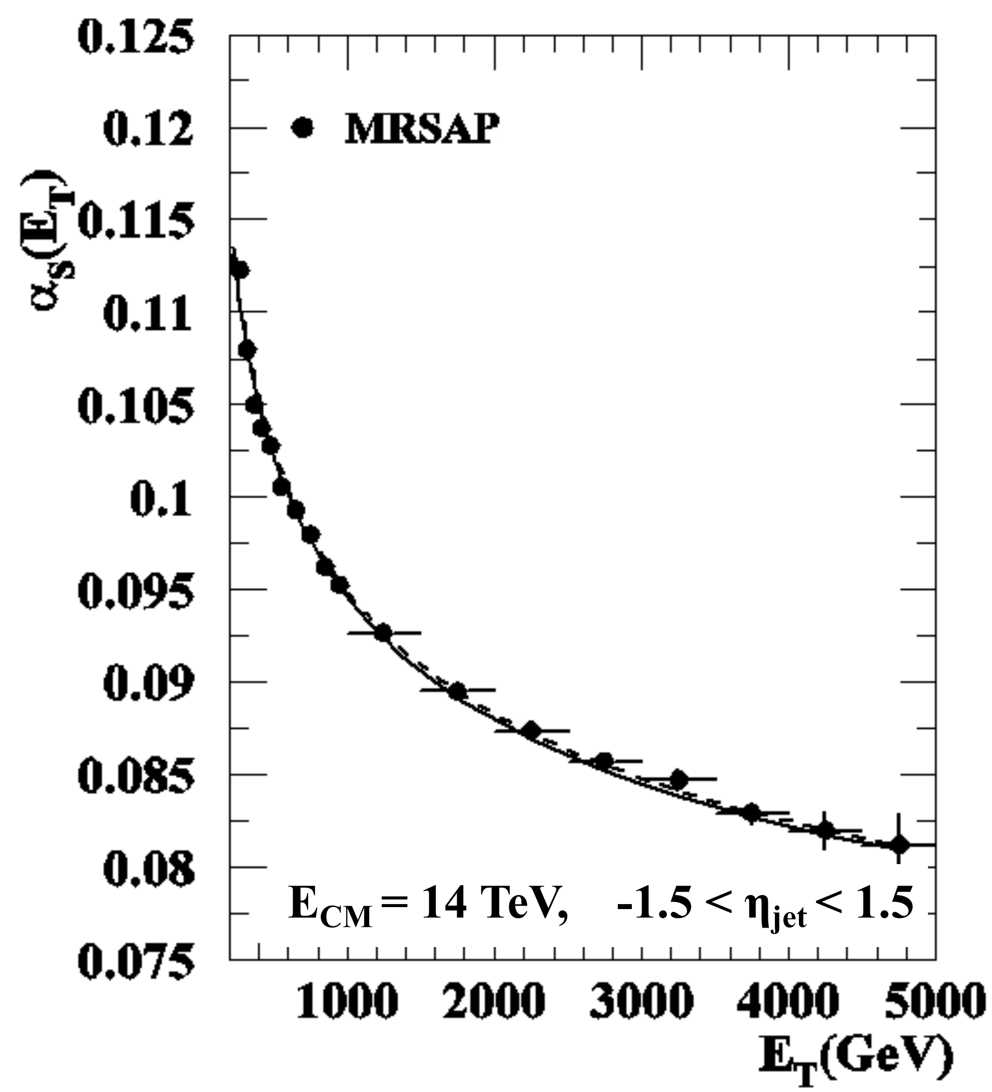
Determination of α_s: scale dependence

- Verification of the running of α_S : check of QCD at the **smallest distance scales yet uncovered**:
  - α_S= 0.118 at 100 GeV
  - α_S~ 0.082 at 4 TeV

- However, measurements of $\boldsymbol{\alpha_S(M_Z)}$ will not be able to compete with precision measurements from e^+e^- and DIS (gluon distribution).

- Differential cross-section for inclusive jet production (NLO)

$$\frac{d\sigma}{dE_T} \sim \alpha_S{}^2(\mu_R)A(E_T) + \alpha_S{}^3(\mu_R)B(E_T)$$



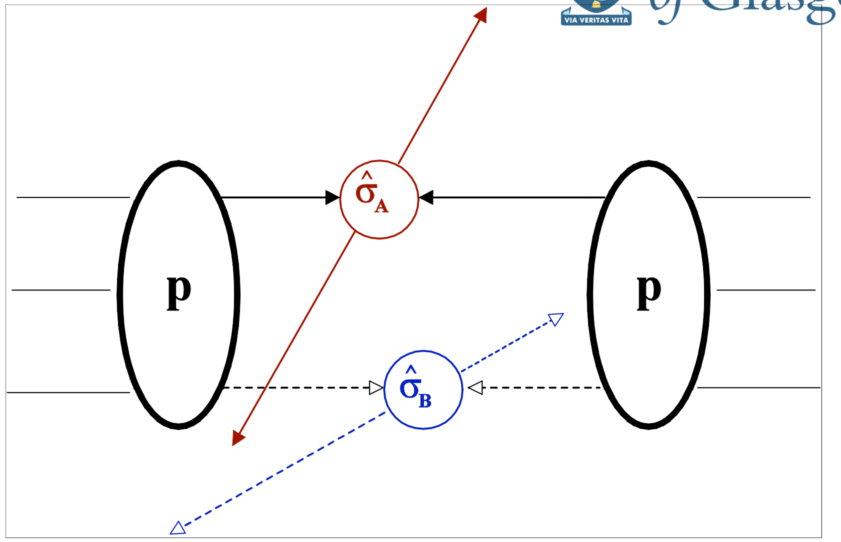
- A and B are calculated at NLO with input p.d.f.'s.

- Fitting this expression to the measured inclusive cross-section gives for each E_T bin a value of $\alpha_S(E_T)$.

- **Systematic uncertainties**:
  - **p.d.f. set (±3%),**
  - **parametrization of A and B,**
  - **renormalization and factorization scale (±7%).**

Multiple Parton Interactions

University of Glasgow



• AFS, UA2 and more recently (and crucially!) CDF, have measured **double parton** interactions.

$$\sigma_D\left(p_T^{\,cut}\right) = m\,\frac{\sigma_A\sigma_B}{2\sigma_{eff}}$$

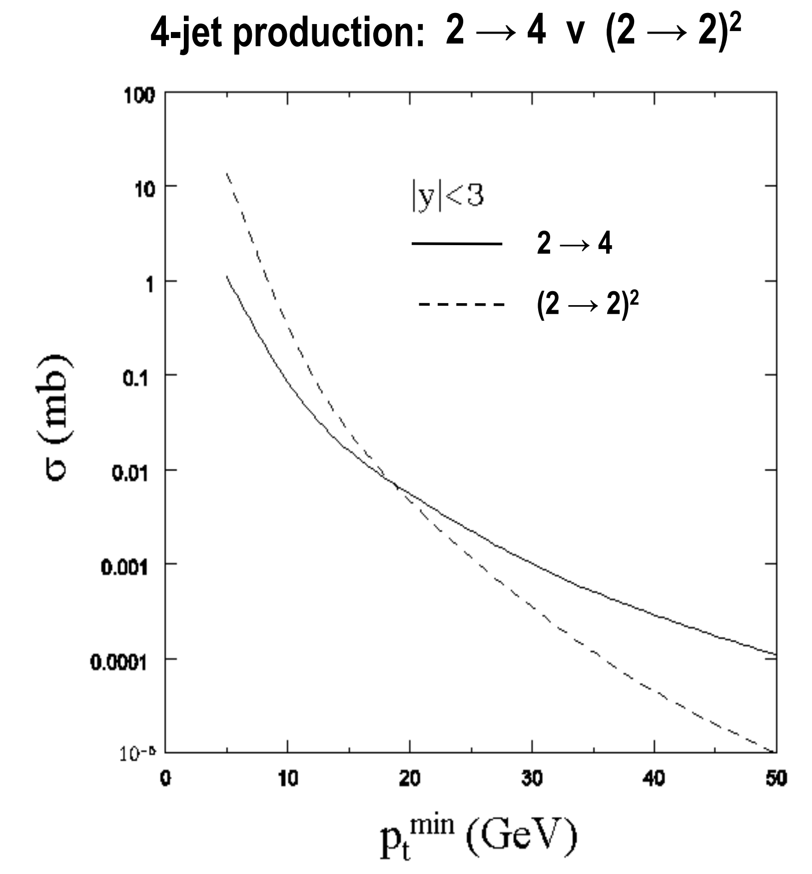
$\sigma_{eff} = 14.5 \pm 1.7$ mb

- σ_{eff} has a geometrical origin;
- parton correlation on the transverse space;
- it is energy and cut-off independent.

• σ_D decreases as $\mathbf{p_T \to \infty}$ and grows as $\mathbf{p_T \to 0}$.

• σ_D increases faster with **s** as compared to σ_S.

Multiple parton collisions are **enhanced** at the LHC!



• **Source of background**:

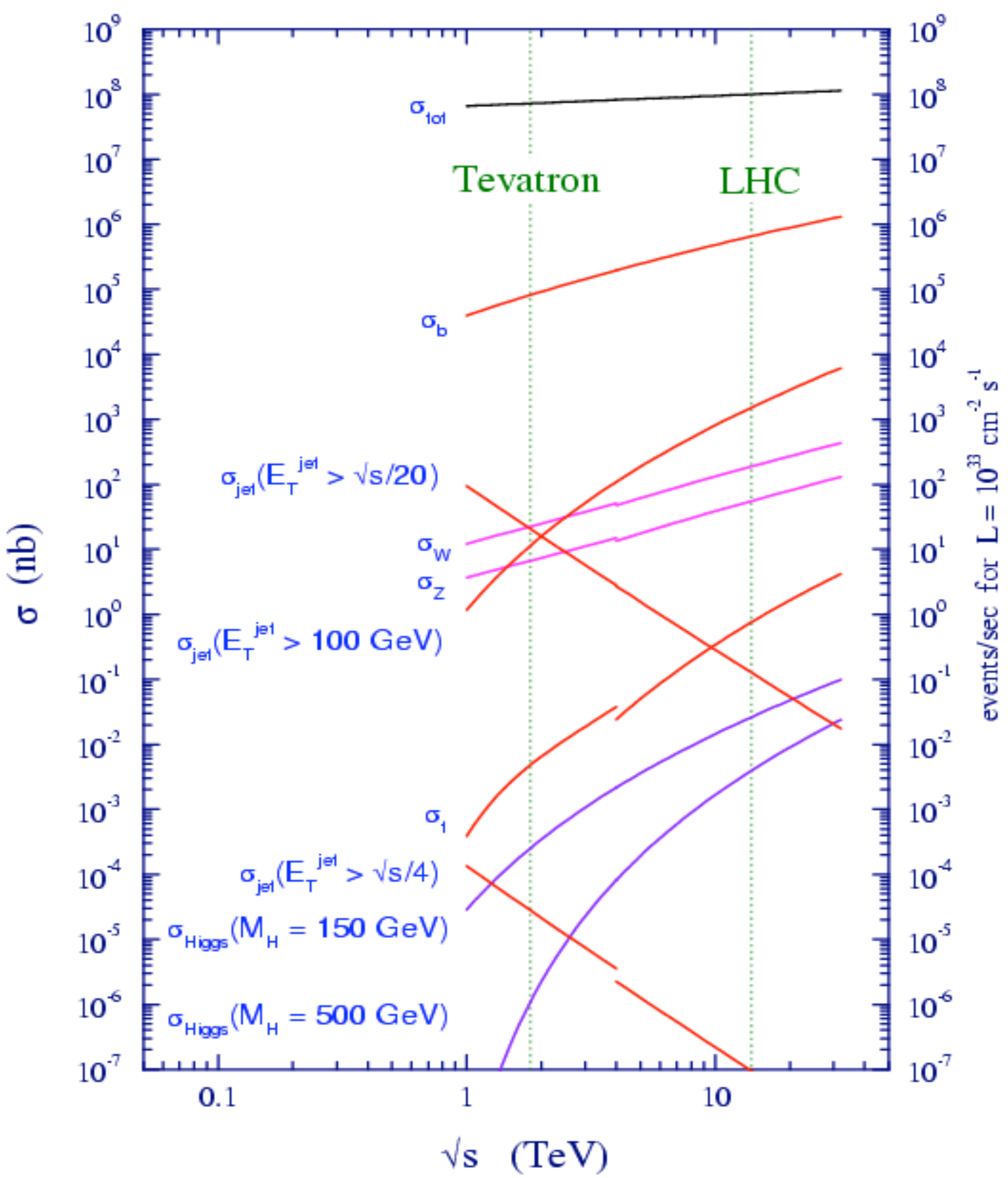
- **WH+X→ (lν) $b\bar{b}$+X,**
- **Z$b\bar{b}$→ (lν) $b\bar{b}$+X,**
- **W + jets, Wb + jets and W$b\bar{b}$ + jets,**
- **$t\bar{t}$ → $llb\bar{b}$,**
- **final states with many jets p_T^{min} ~ 20 – 30 GeV.**

Summary:

- LHC will probe QCD to unexplored kinematic limits;
- Jet studies (test of pQCD, constrain p.d.f.'s, physics studies);
- Luminosity uncertainties can be reduced by measurements of relative luminosities: high-Q^2 and wide x-range;
- Prompt-photon production will lead to improved knowledge of background levels ($H \to \gamma\gamma$), $f_g(x)$ and parton dynamics;
- α_s at high-energy scales (test of the running of α_s);
- Multiple parton scattering: source of background and/or new physics channels;
- Minimum-bias and the underlying event: improved understanding of events dominated by soft processes.

Backup

SM at the LHC: what can be done with early data?



Process	σ(nb)	Ns^{-1}	$\mathcal{L}=10pb^{-1}$	$\mathcal{L}=10fb^{-1}$
Minimum bias	10^8	10^7	10^{12}	$\sim10^{15}$
Inclusive jets – p_T>200GeV	100	100	10^6	$\sim10^9$
$W \rightarrow e\nu$	15	15	10^5	$\sim10^8$
$Z \rightarrow e^+e^-$	1.5	1.5	10^4	$\sim10^7$
Dibosons	0.2	10^{-3}	10	10^4

Will we have enough events?

If ~50% of events are unusable, we still have enough for precision measurements !

Need to understand the detector.