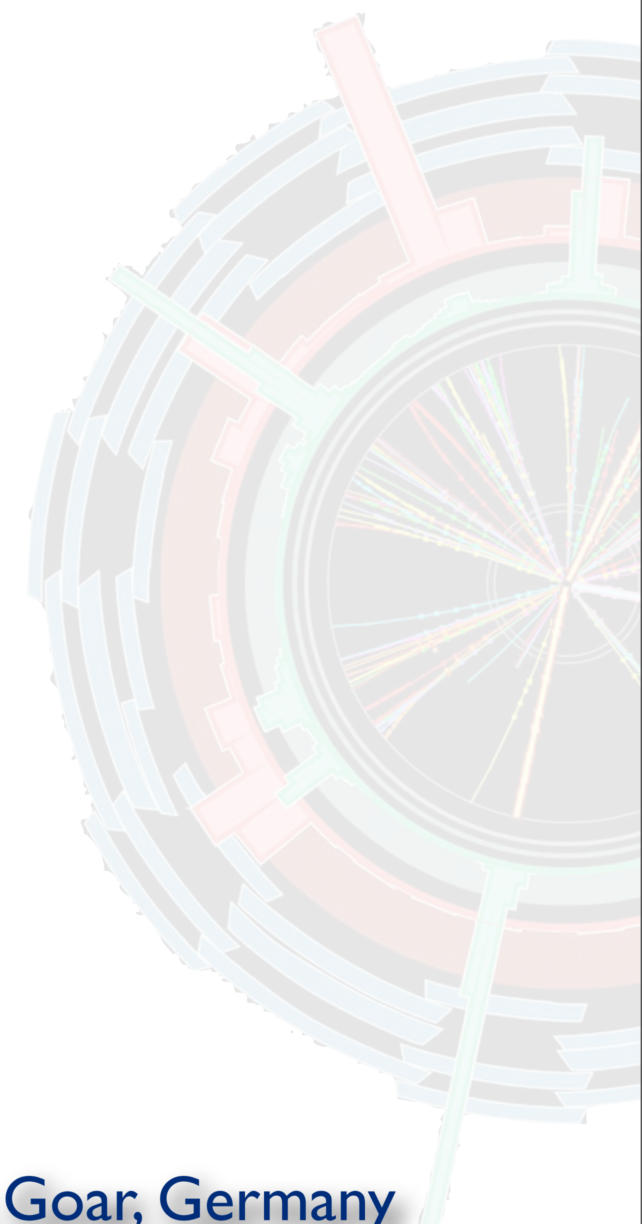
QCD at ATLAS

Arthur M. Moraes
University of Glasgow
(on behalf of the ATLAS Collaboration)



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

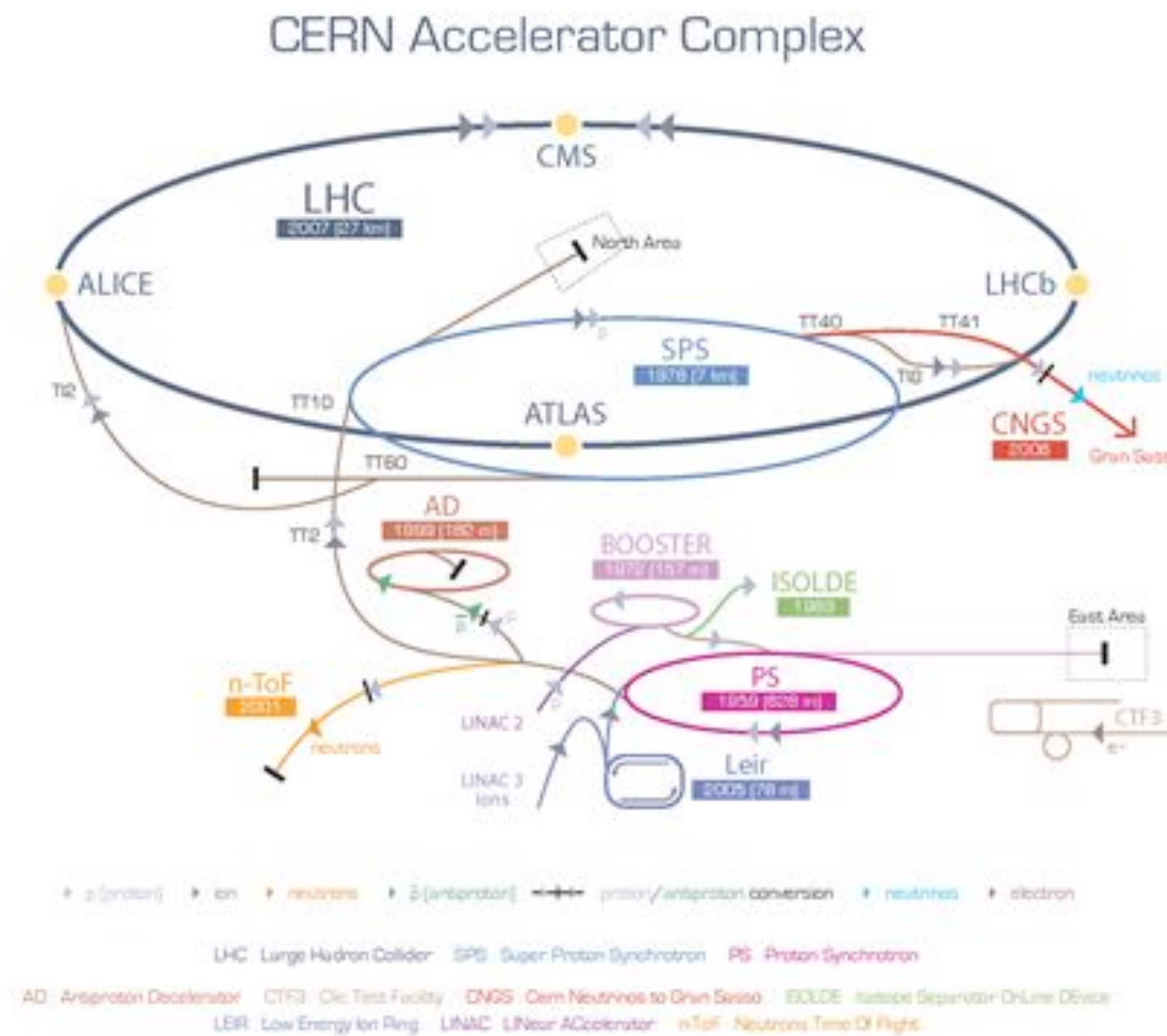
d. Direct photon production

e. Measurement of the α_s at very large scales

f. Multi-parton interactions

III. Summary

The *Large* *Hadron* *Collider*



- p-p collisions at $\sqrt{s}=14$TeV (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 Toroidal LHC ApparatuS*

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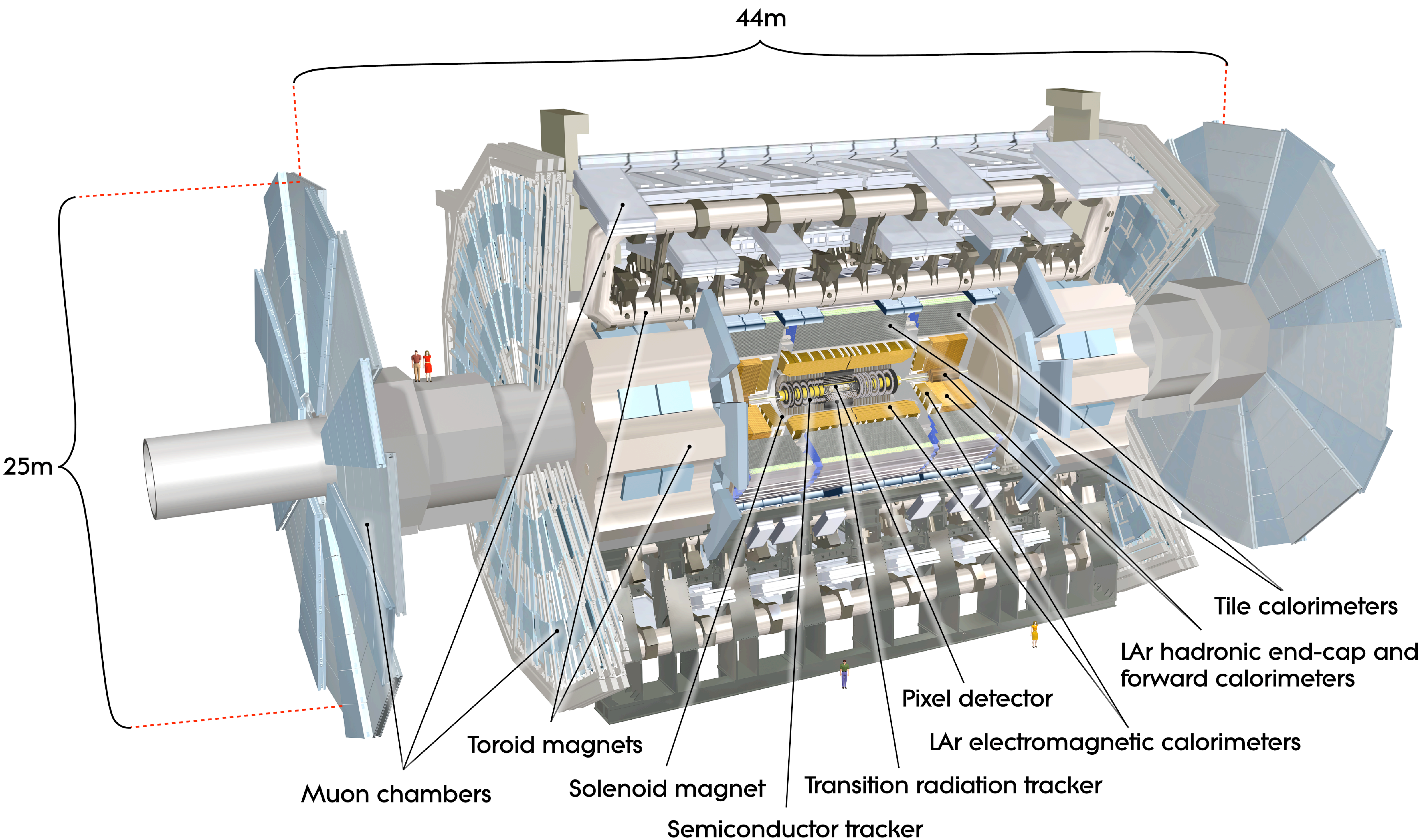
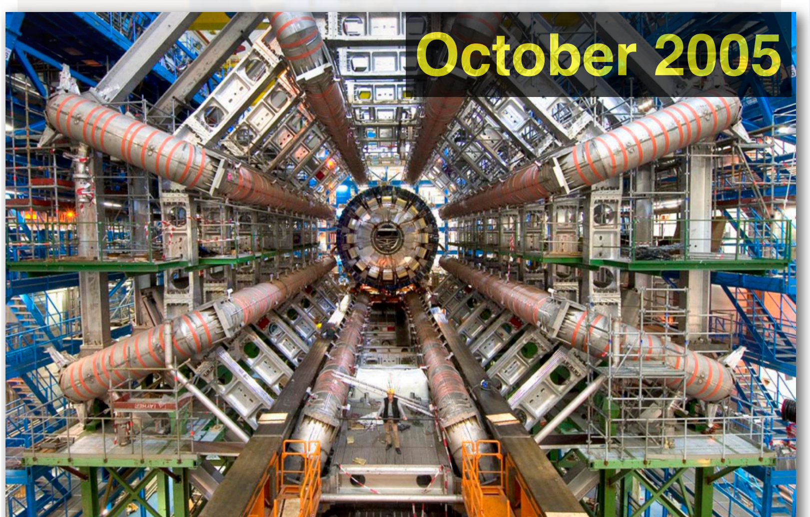
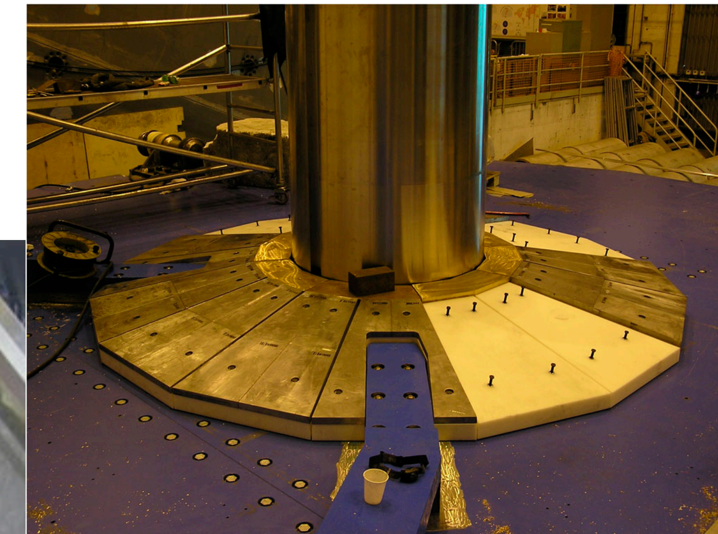


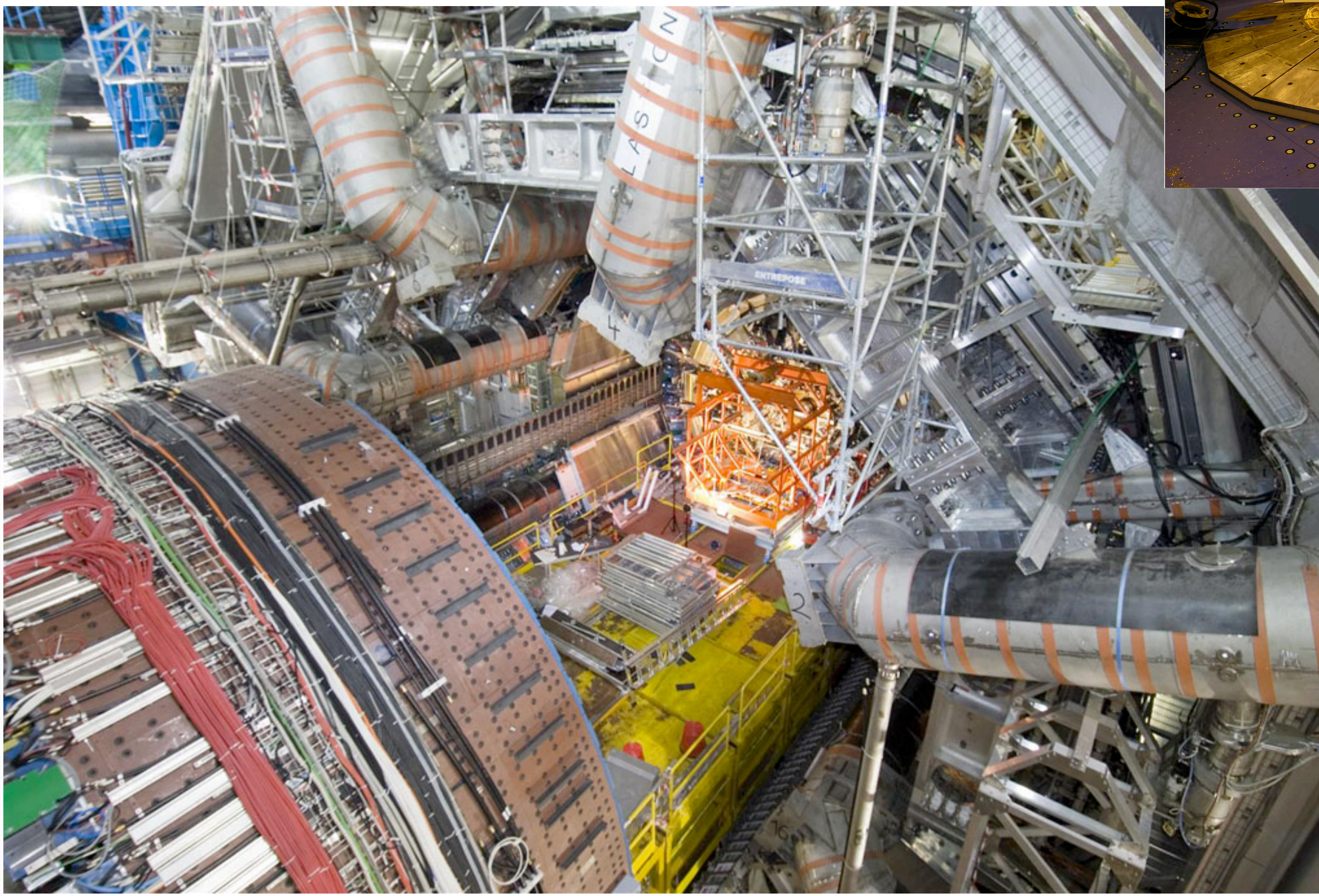
ATLAS Installation Progress



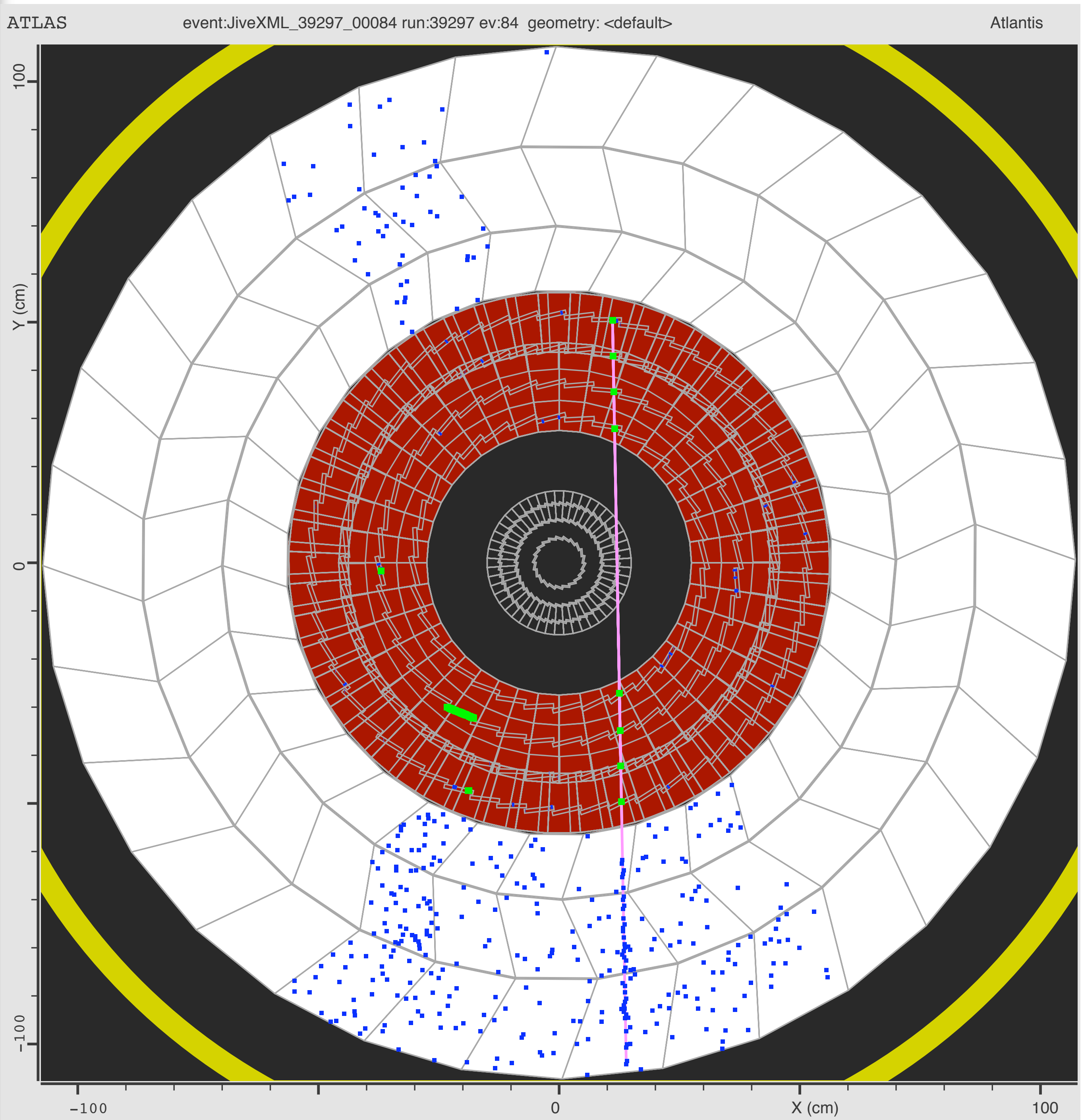
Status on 29th of February 2008!

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

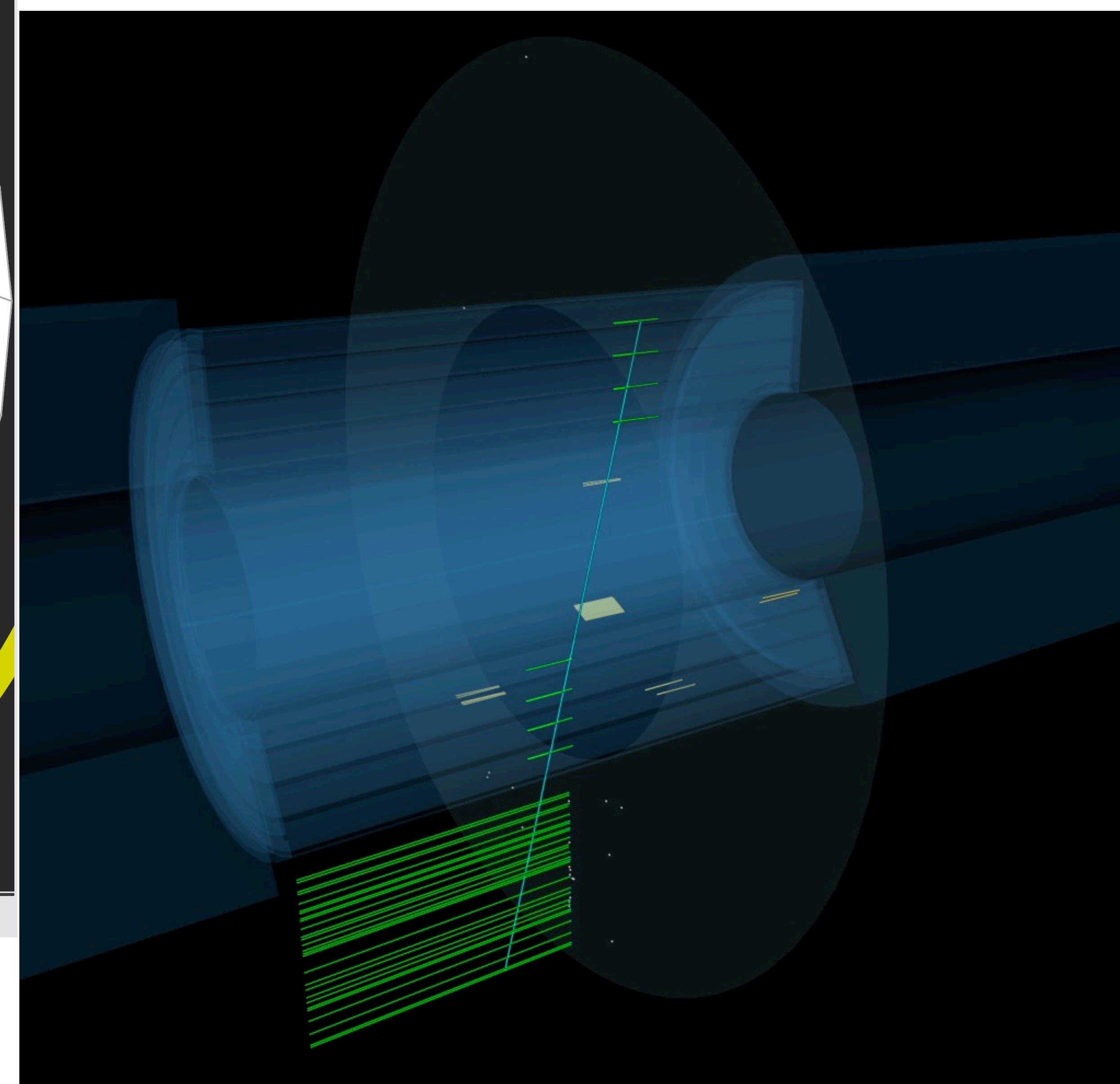




Track from cosmic ray event detected by SCT and TRT systems



- 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	$\sim 10^9$
$W \to e\nu$	15	15	10^5	$\sim 10^8$
$Z \to e^+e^-$	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

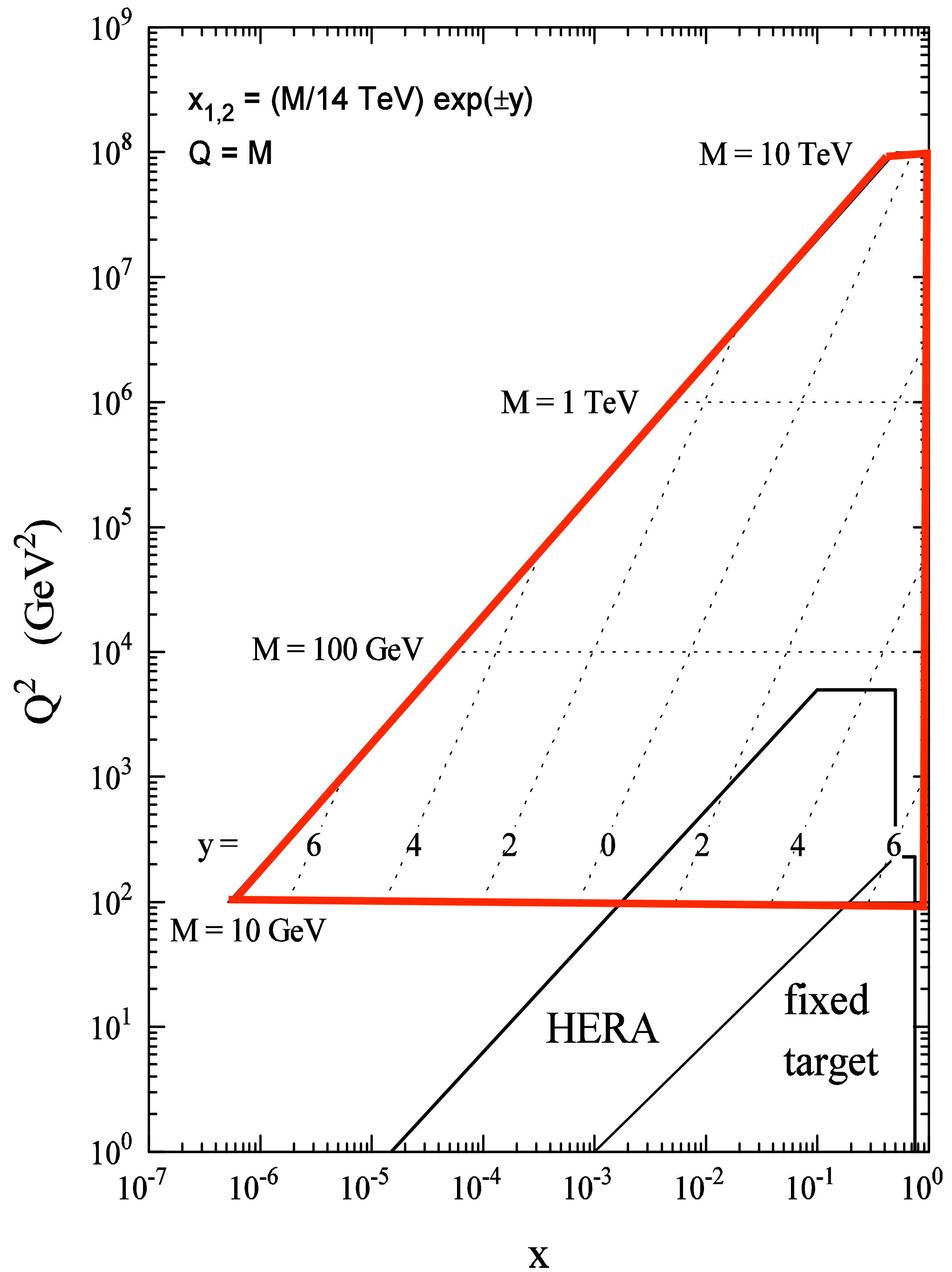
- Essentially all physics at LHC are connected to the interactions of quarks and gluons (small & large transferred momentum).

- 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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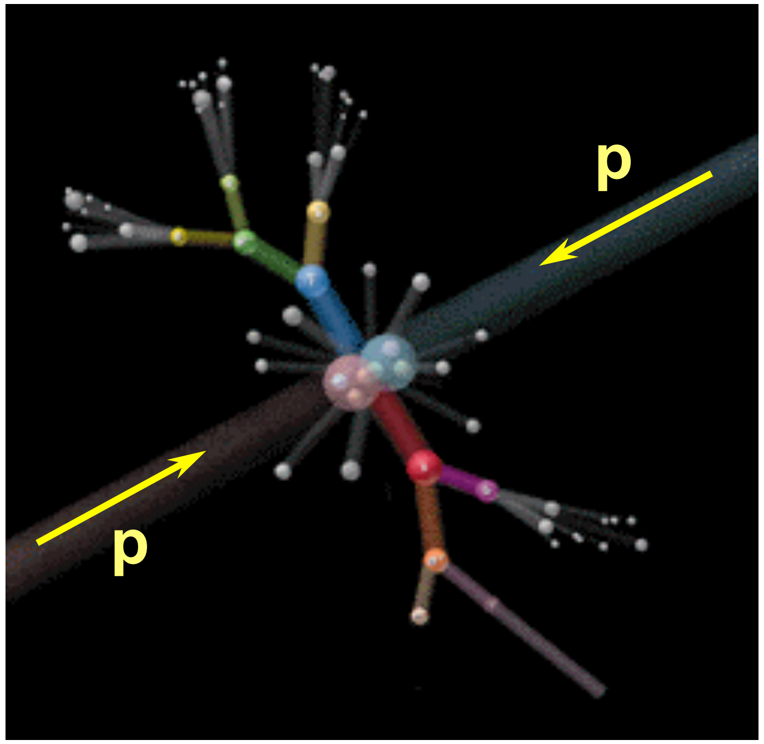
  - Hard processes (high-p_T): well described by perturbative QCD
  - Soft interactions (low-p_T): require non-perturbative phenomenological models



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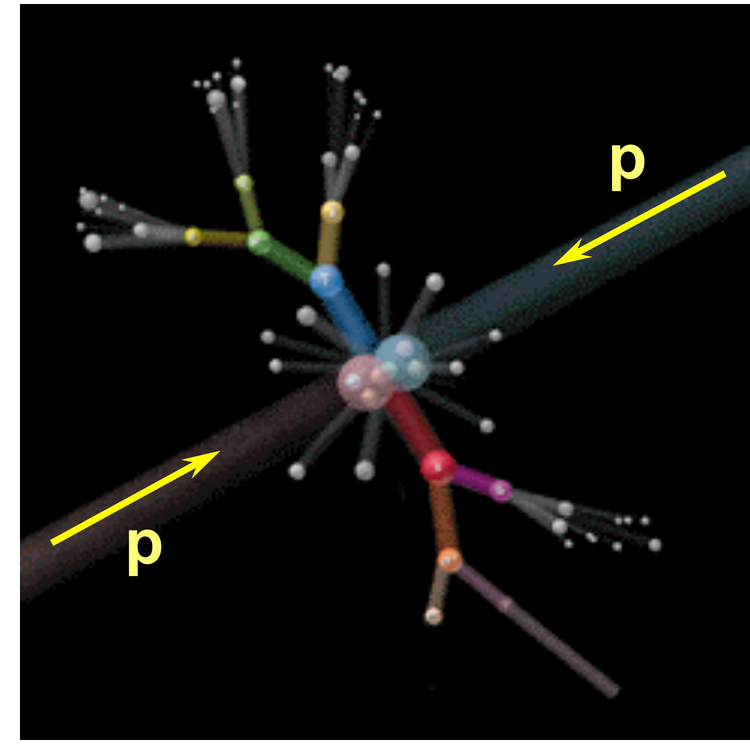
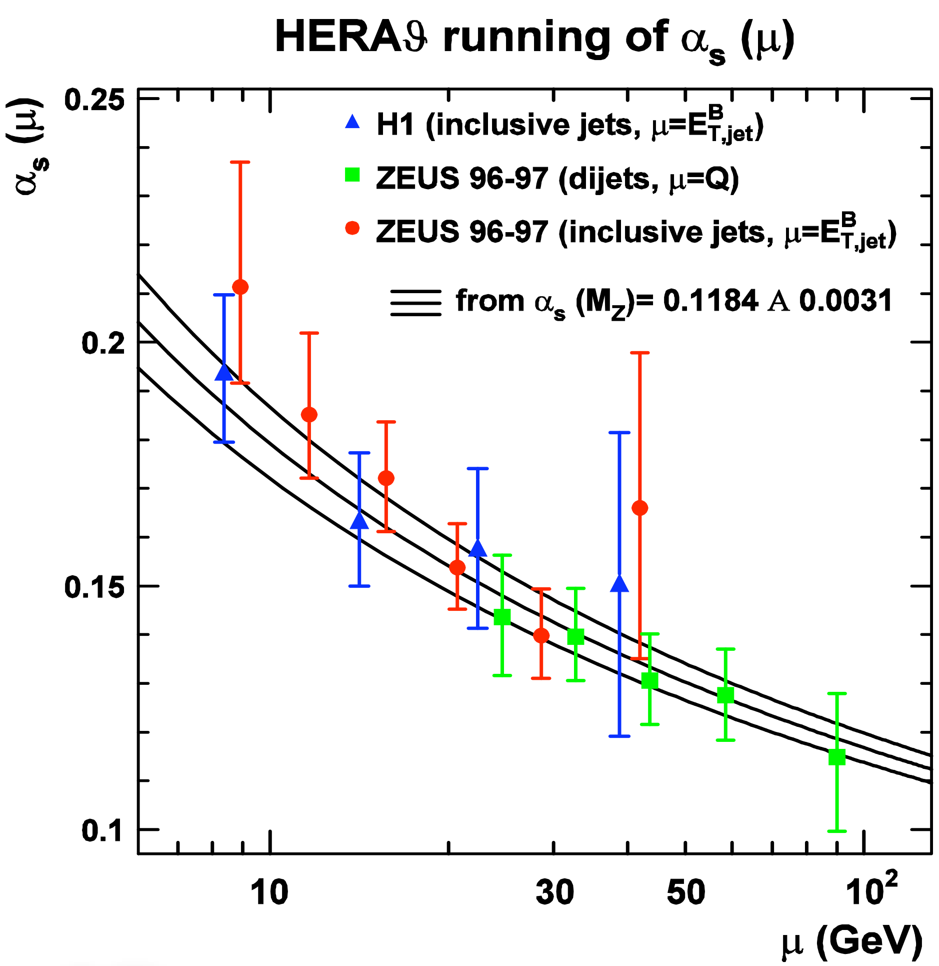




Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,…

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

Minimum bias measurements

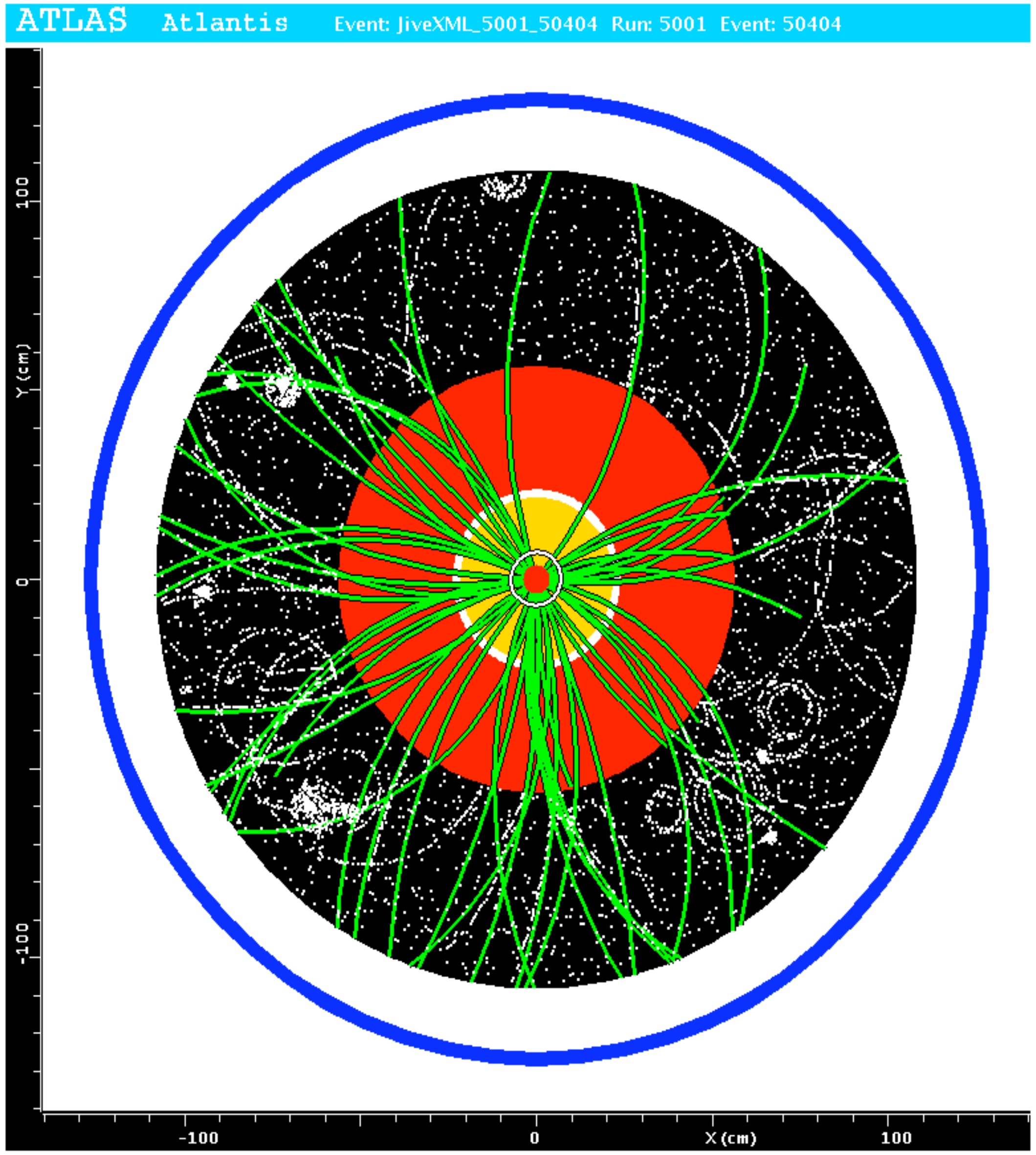
- **Experimental definition**: depends on the experiment's **trigger**!
- "Minimum bias" is usually associated to **non-single-diffractive events** (NSD), e.g. ISR, UA5, E735, CDF,…

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

σ_{tot} ~ 102 - 118 mb (PYTHIA) (PHOJET)

minimum bias event ($\sigma_{d.dif} + \sigma_{n.dif}$)

σ_{NSD} ~ 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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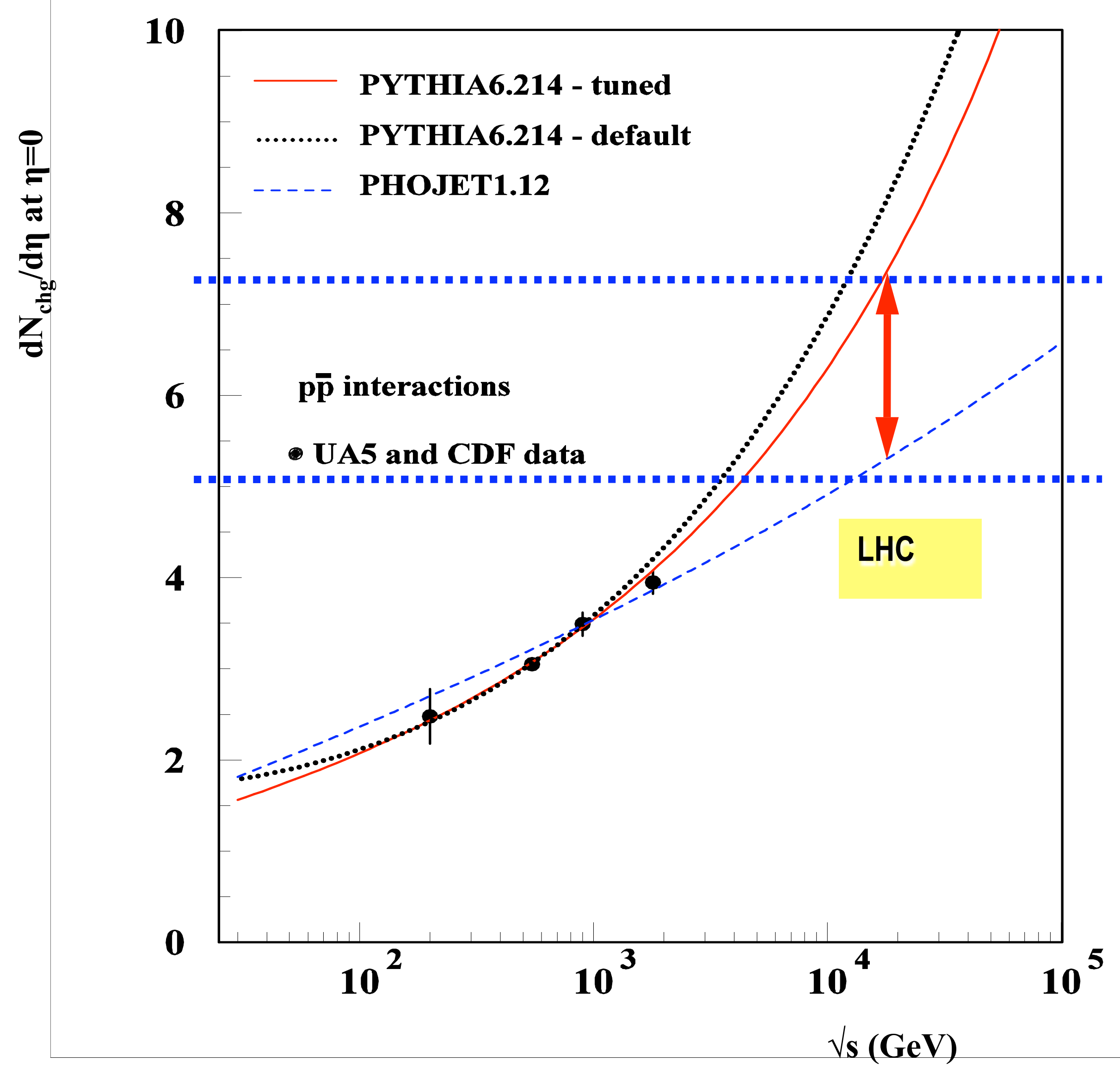

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- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

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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(strategy for low luminosity runs!)

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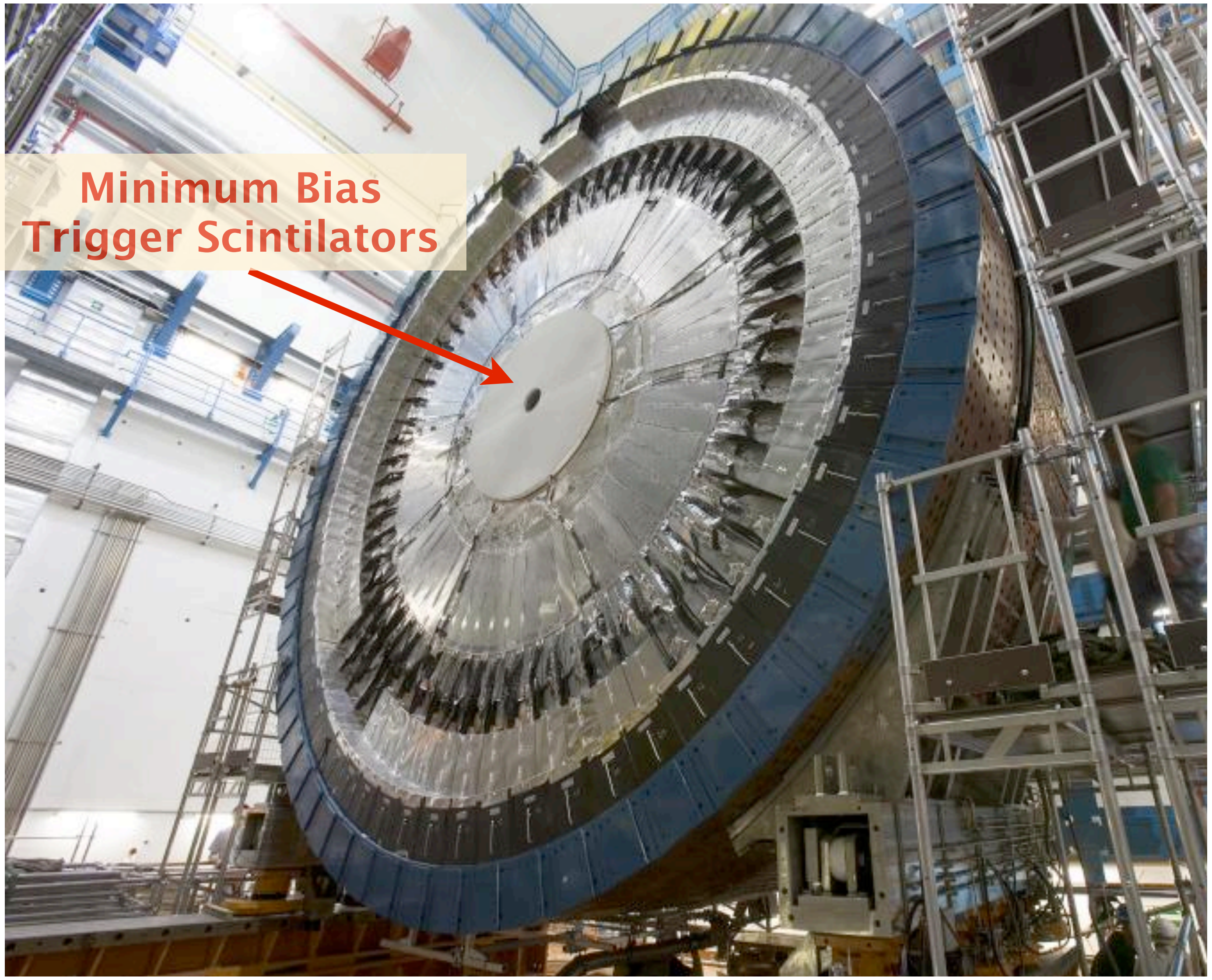
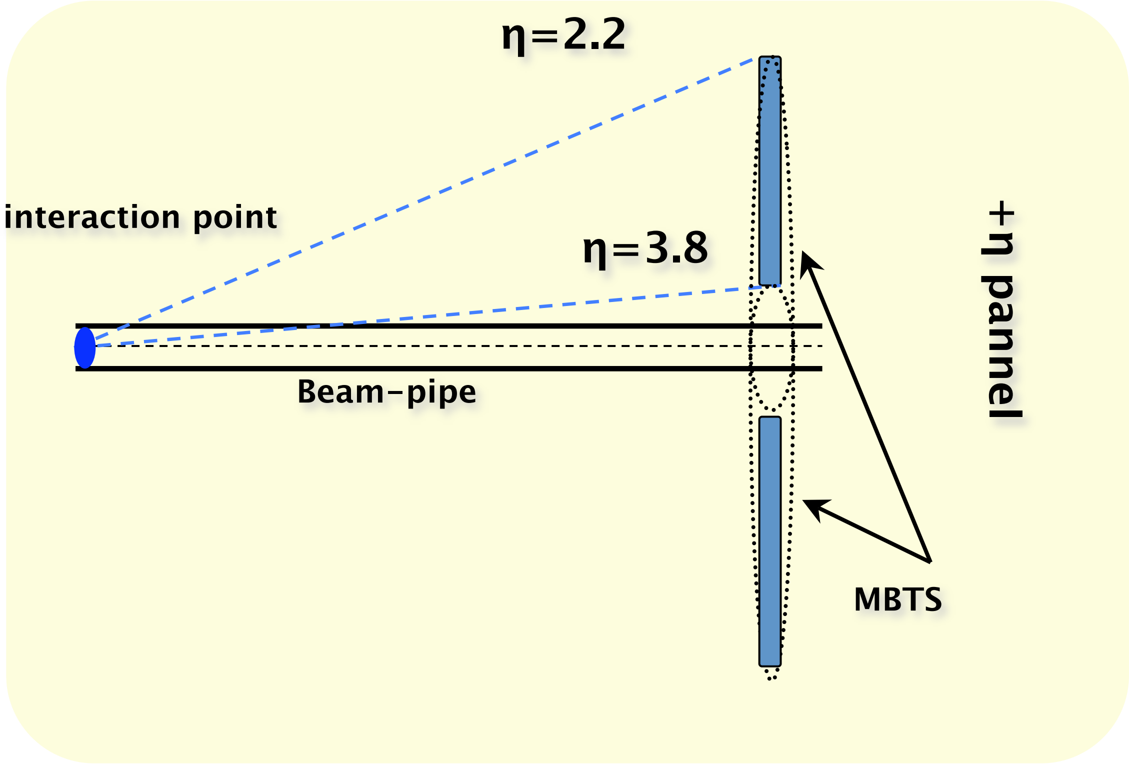
What do we need to separate?

- **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 $L\sim10^{33}cm^{-2}s^{-1}$ and greater).

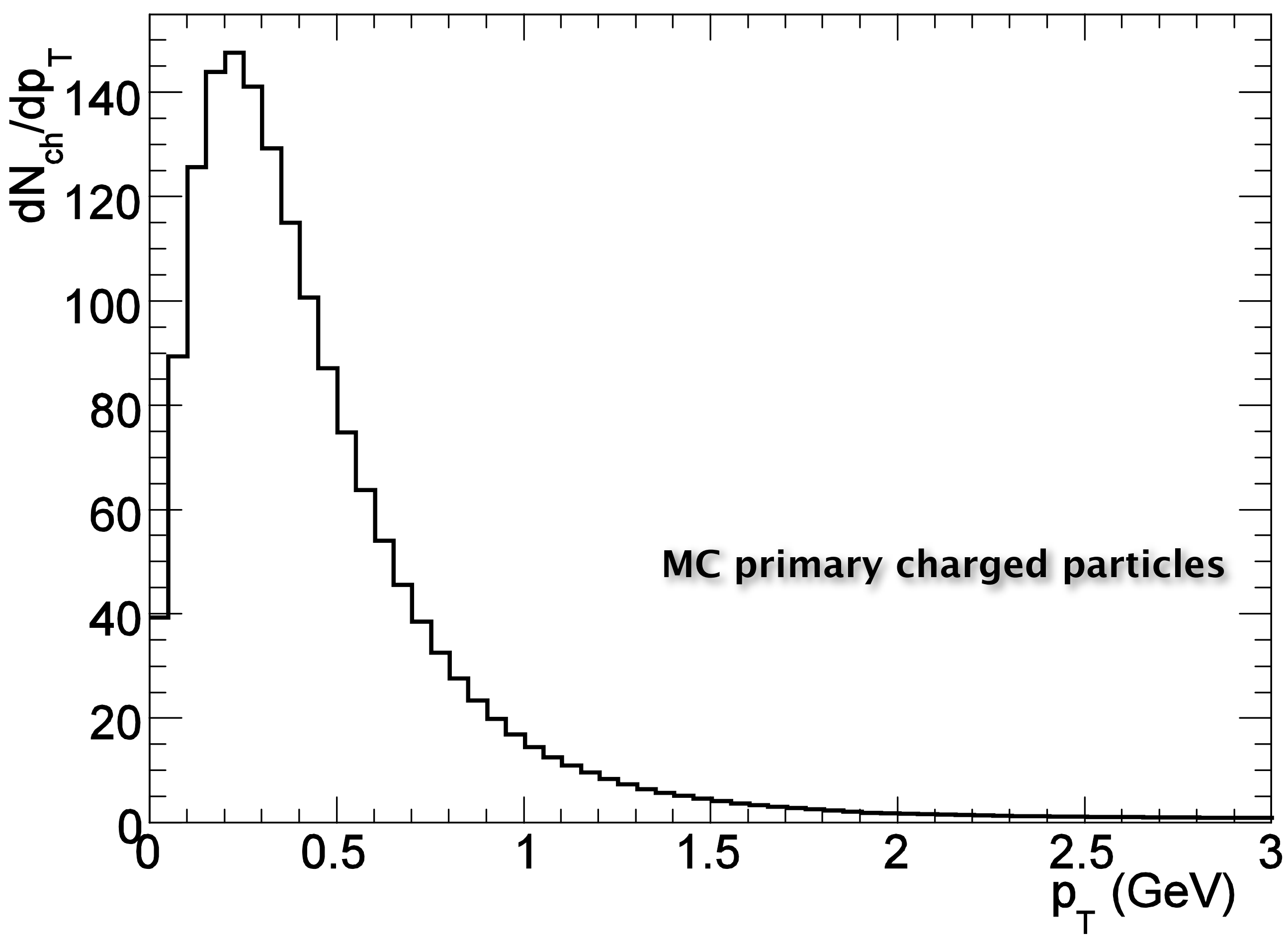
ATLAS trigger for minimum bias events (MBTS)





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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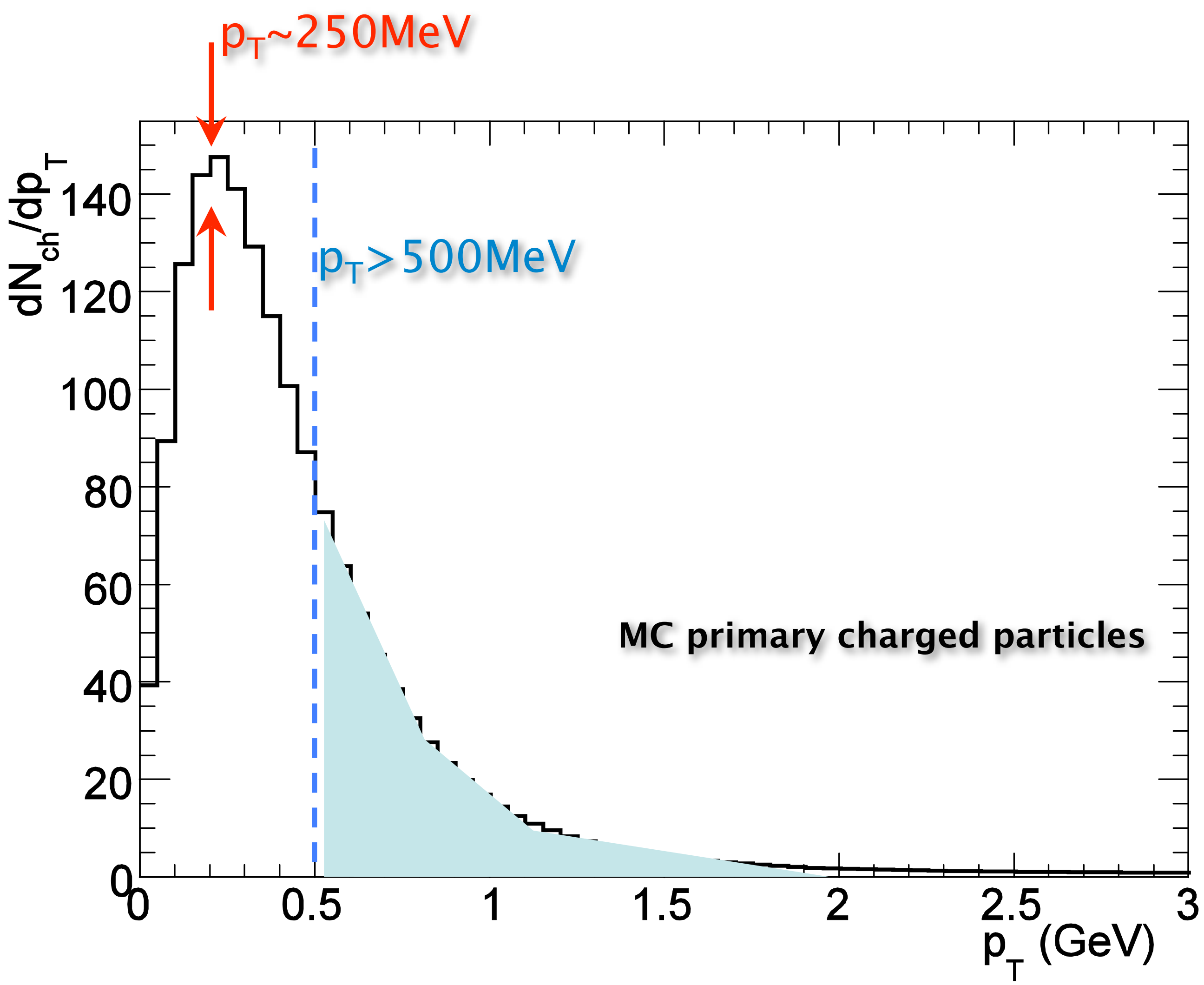
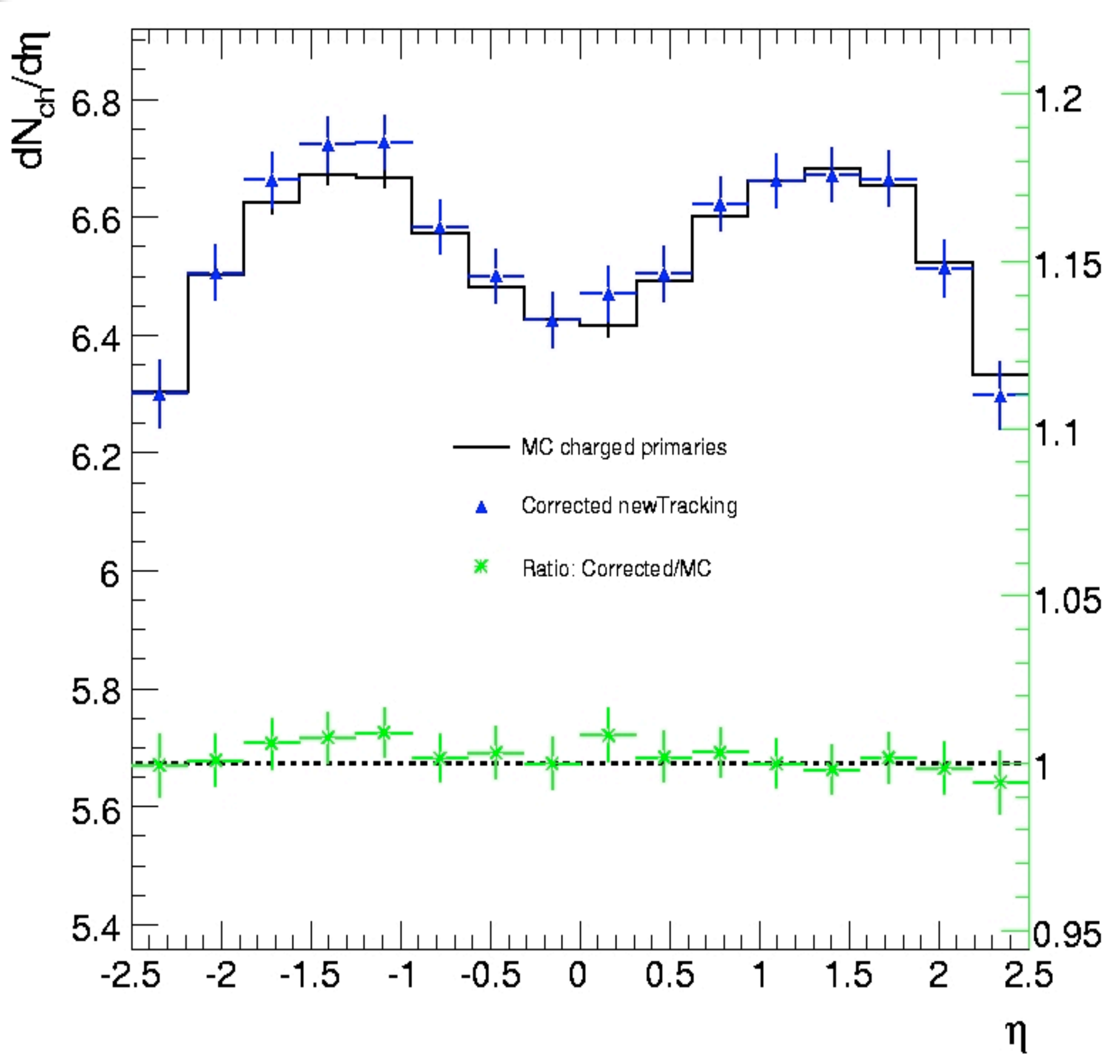


- Work is being done to push this limit to p_T ~ 100 – 200 MeV;
- Avoid large extrapolation factors for measurements such as $dN_{ch}/d\eta$.

Reconstructing minimum bias events

MC charged primaries & track p_T > 150MeV

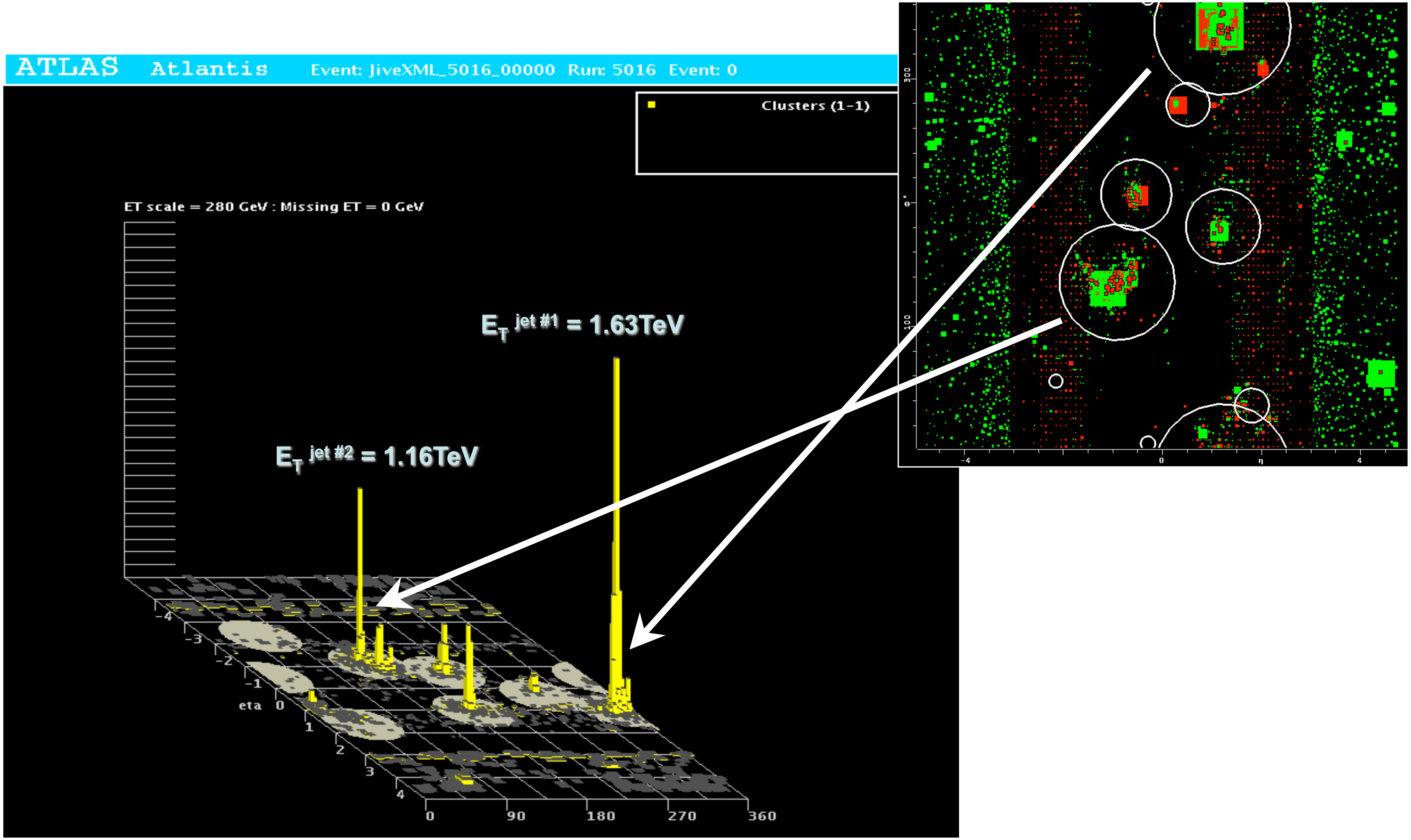


Summary of systematic uncertainties

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

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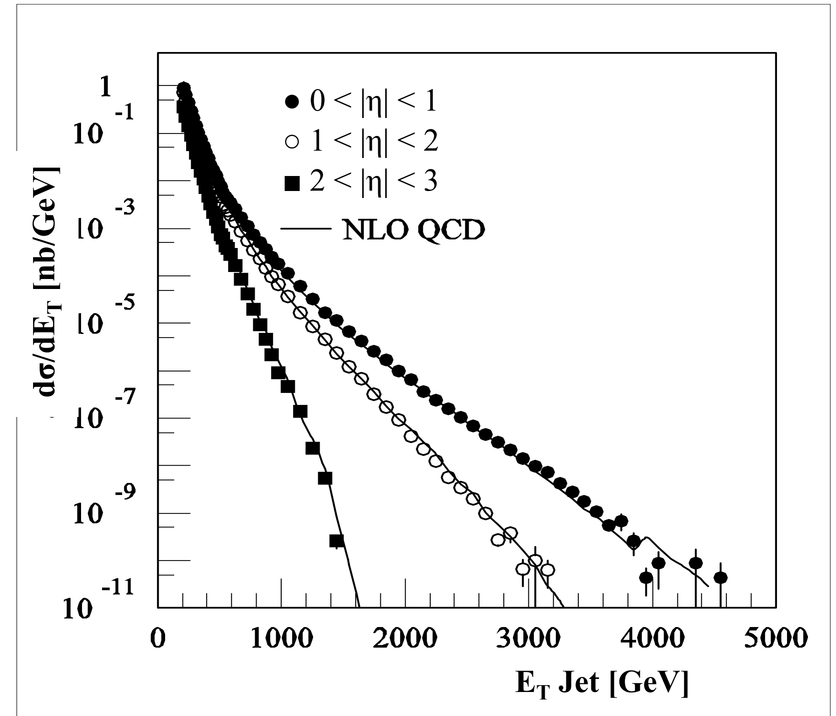
L = 30 fb^{-1}

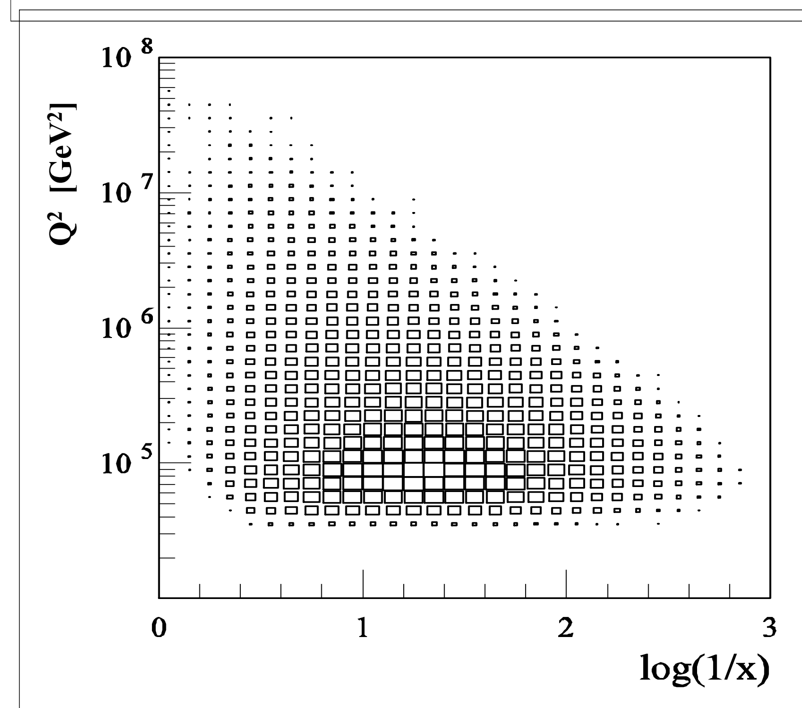
Jet E_T	N_{events}
> 1 TeV	4 x 10^5
> 2 TeV	3 x 10^3
> 3 TeV	40

- 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: $\boldsymbol{\alpha_S(M_Z)}$ 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 $t\bar{t}$ 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.





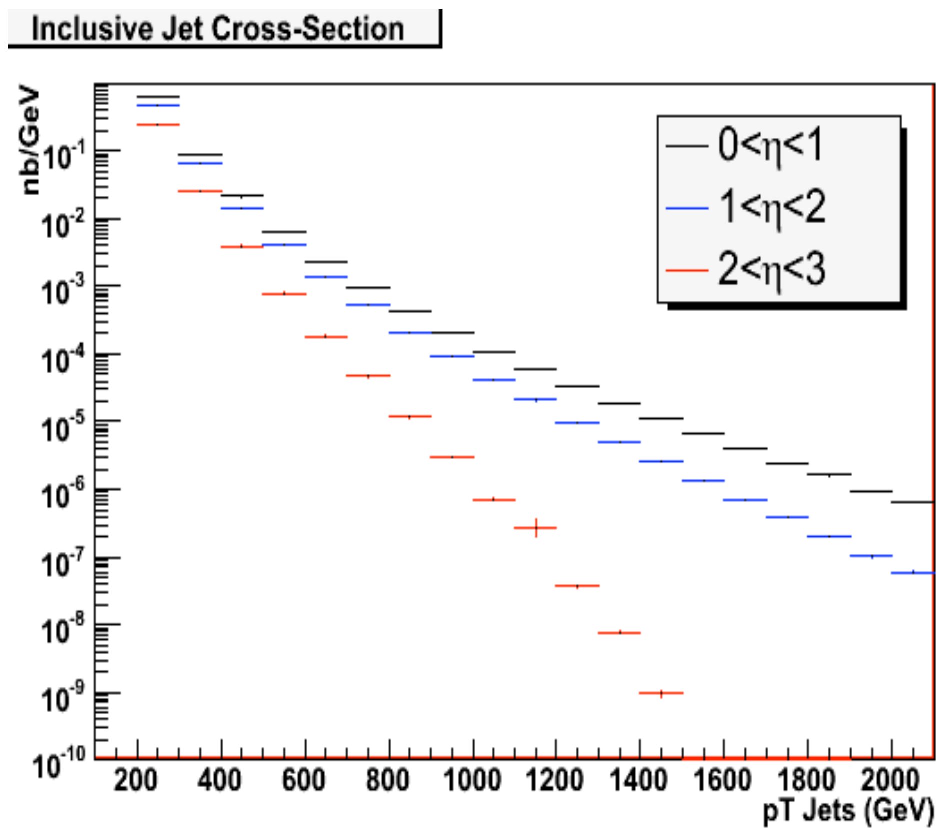
At the LHC the statistical uncertainties on the jet cross-section will be small.

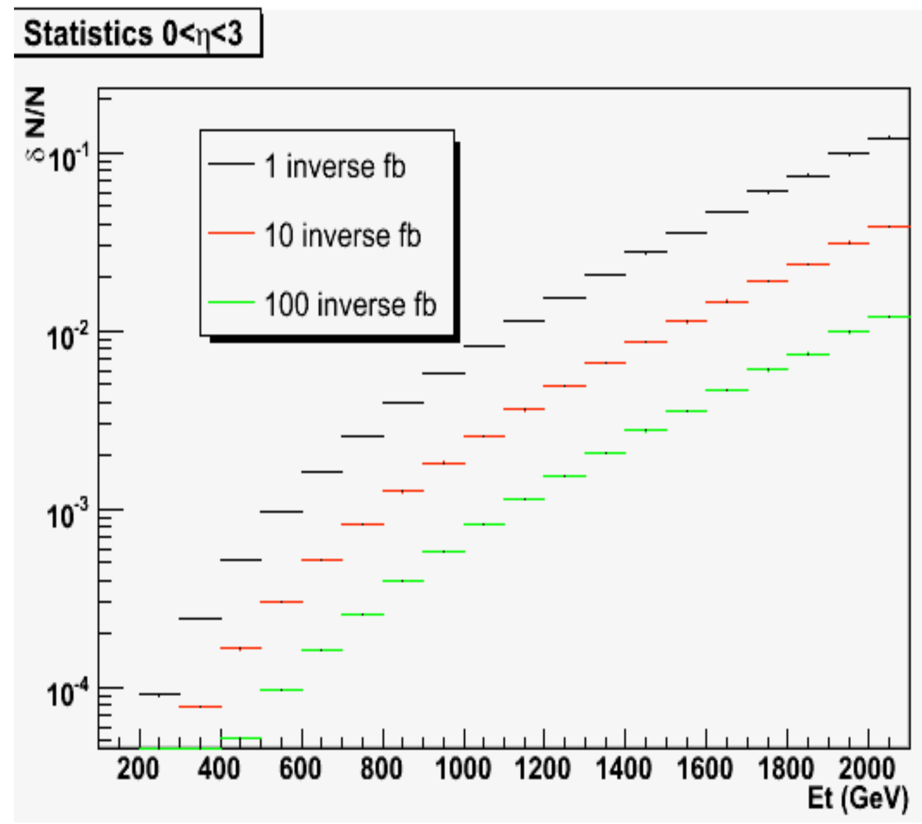
Inclusive jet cross-section

- 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!

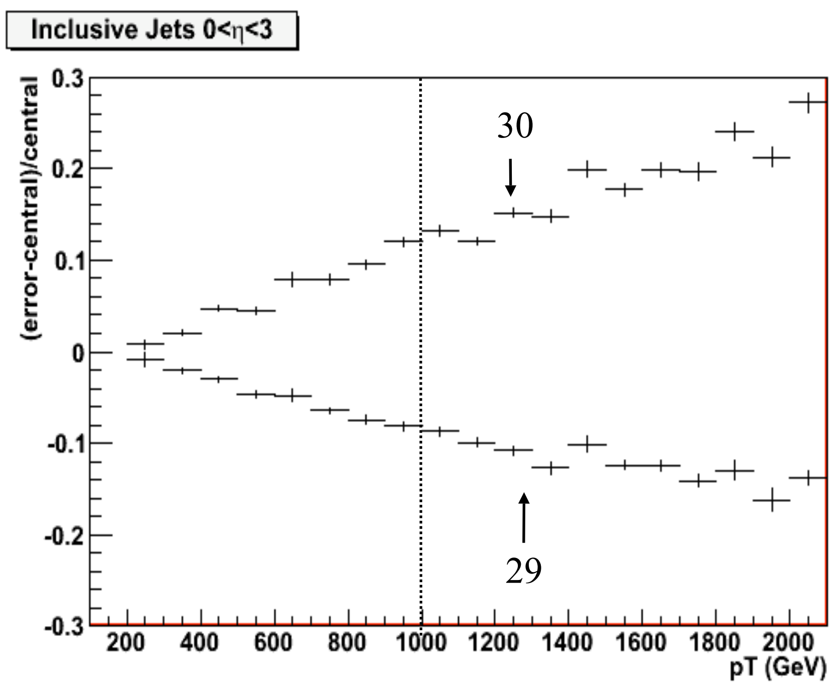




Constraining PDFs with early jet measurements

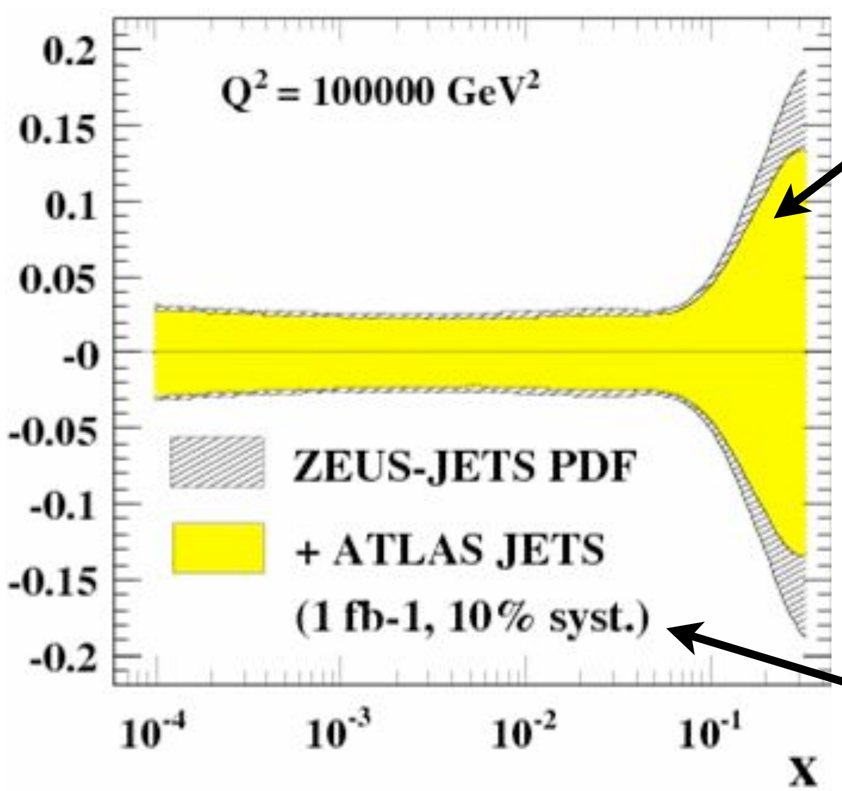
PDF fitting using pseudo-data

- 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:

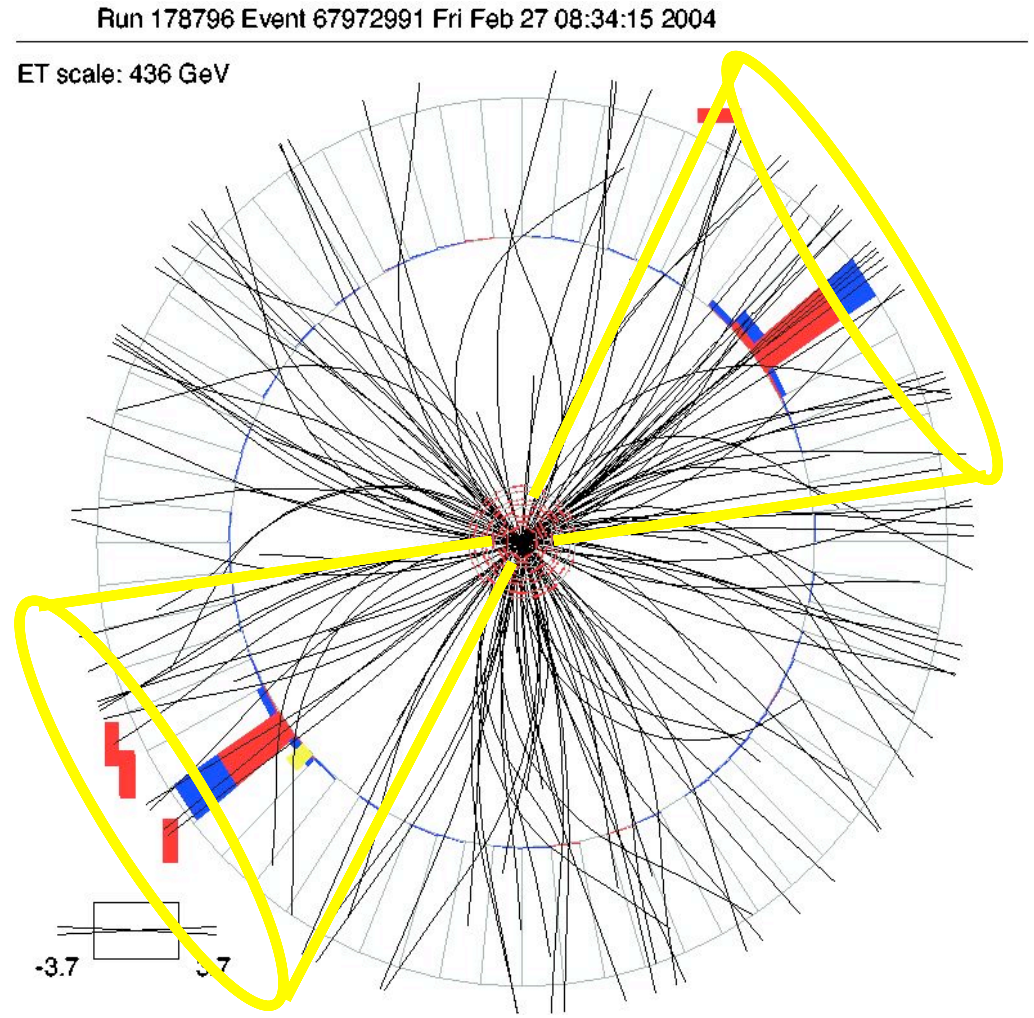


Preliminary indications suggest that ATLAS data can constrain the high x-gluon.

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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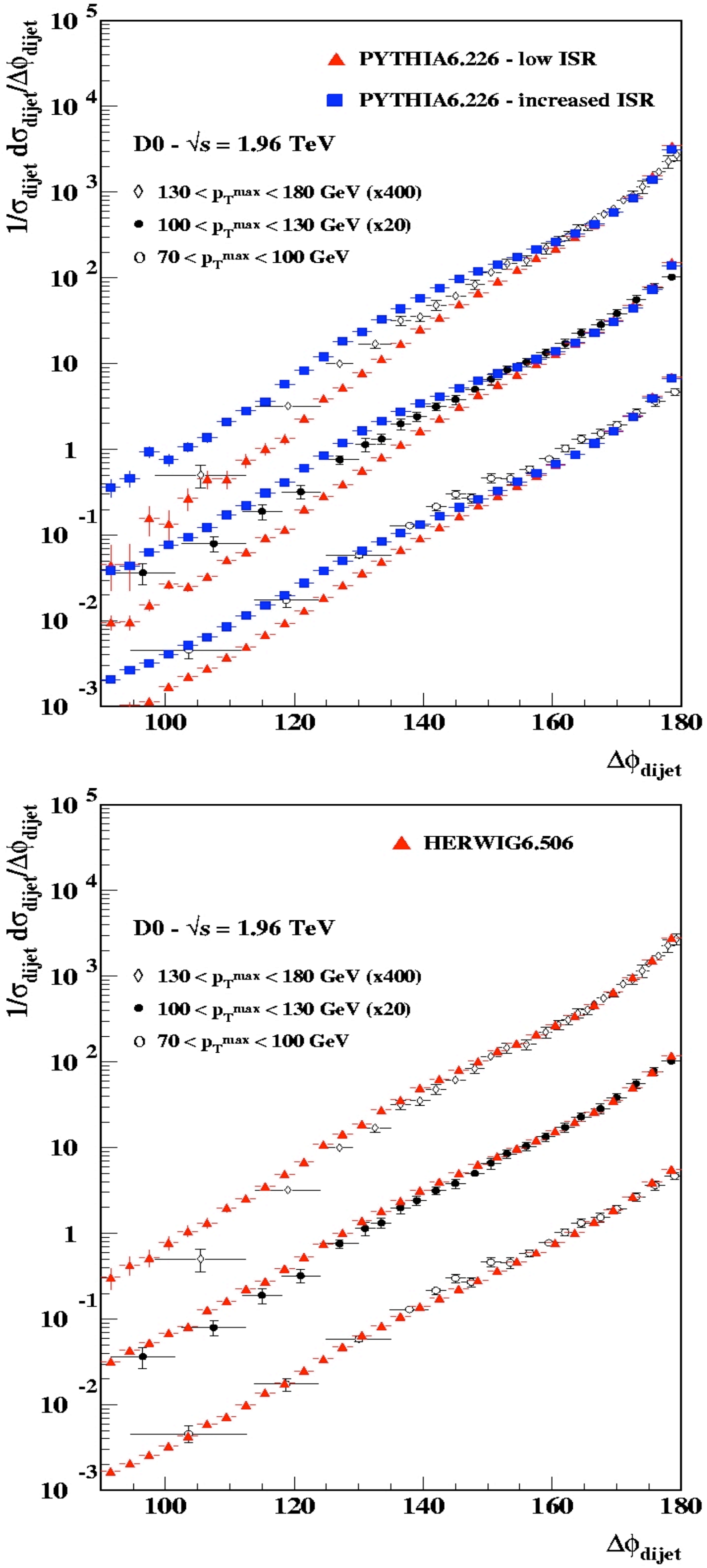

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Azimuthal di-jet decorrelation with reconstructed jets

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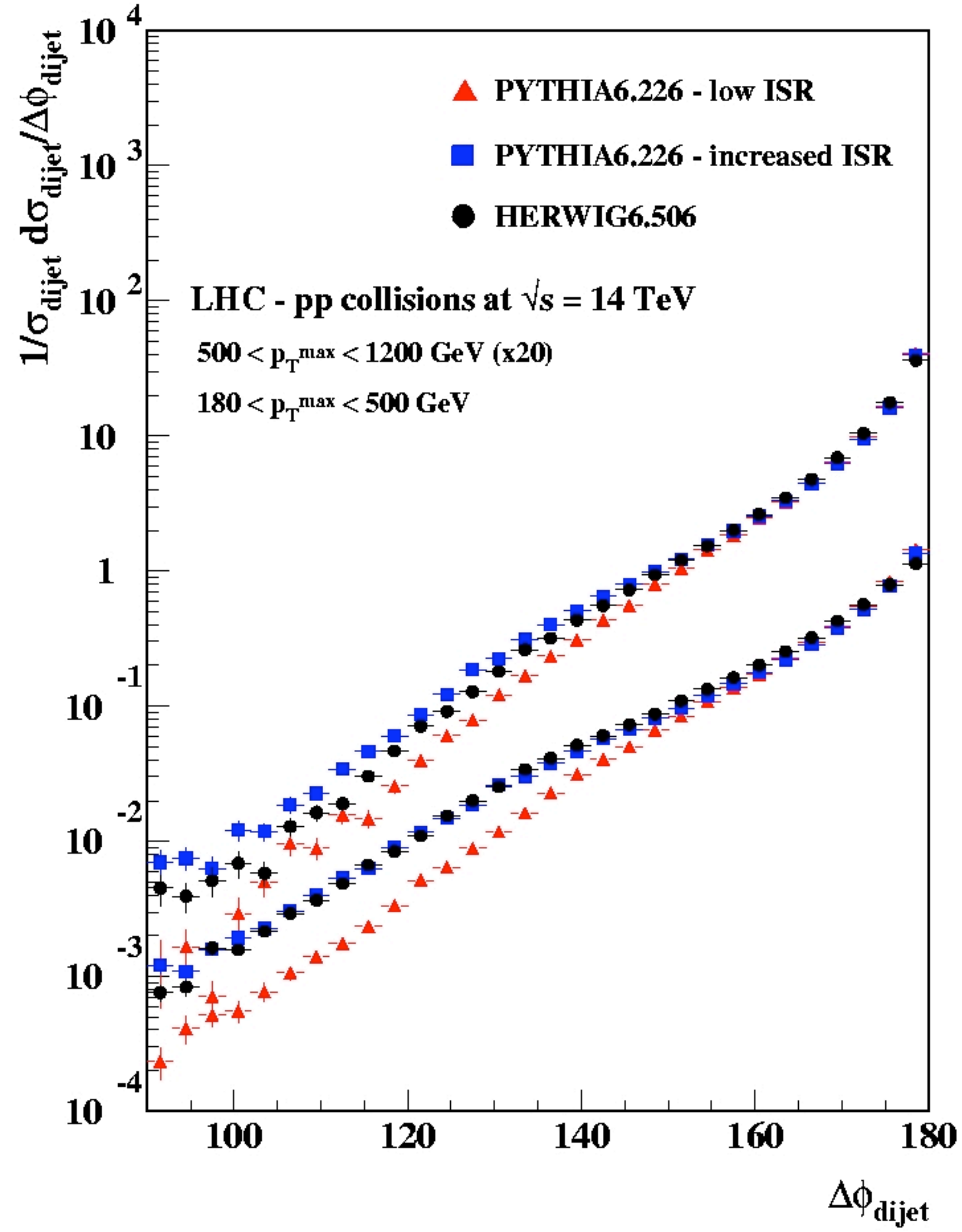

ATL-PHYS-PUB-2006-013

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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

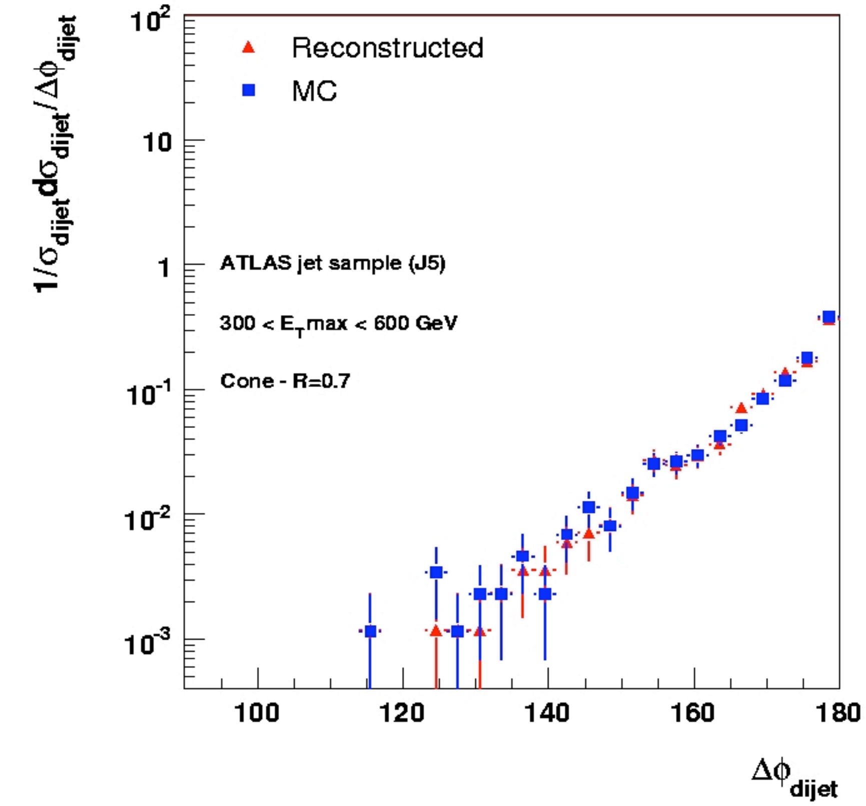
Selecting di-jet events:

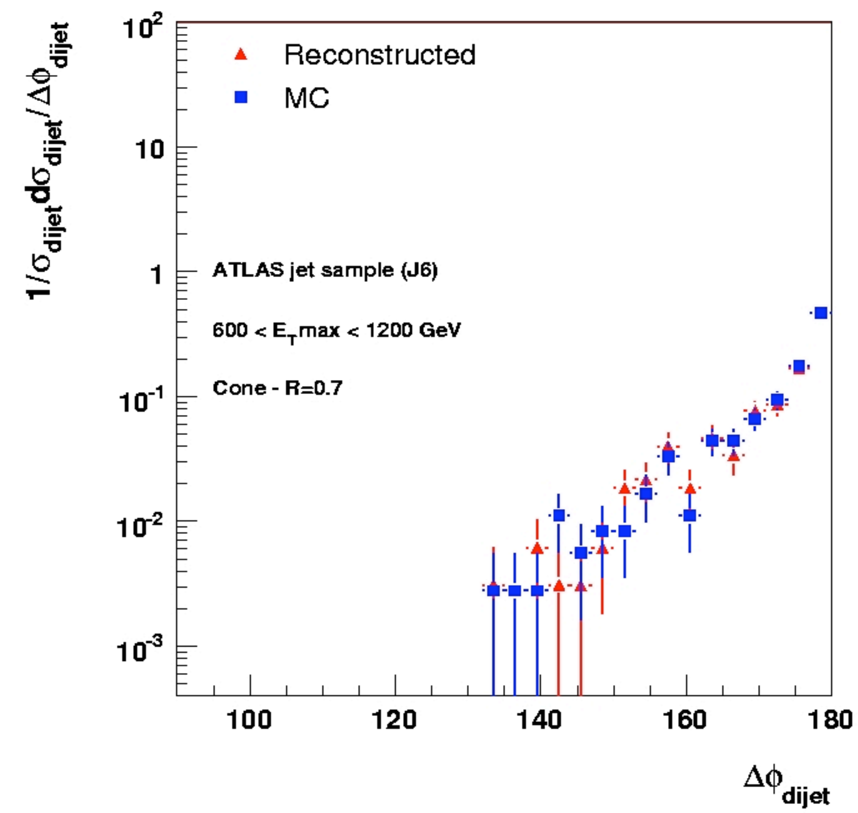
Cone jet algorithm (R=0.7)
$N_{jets} = 2$,
$|\eta_{jet}| < 0.5$,
$E_T^{jet\#2} > 80$ GeV,

Two analysis regions:

$300 < E_T^{MAX} < 600$ GeV → J5

$600 < E_T^{MAX} < 1200$ GeV → J6





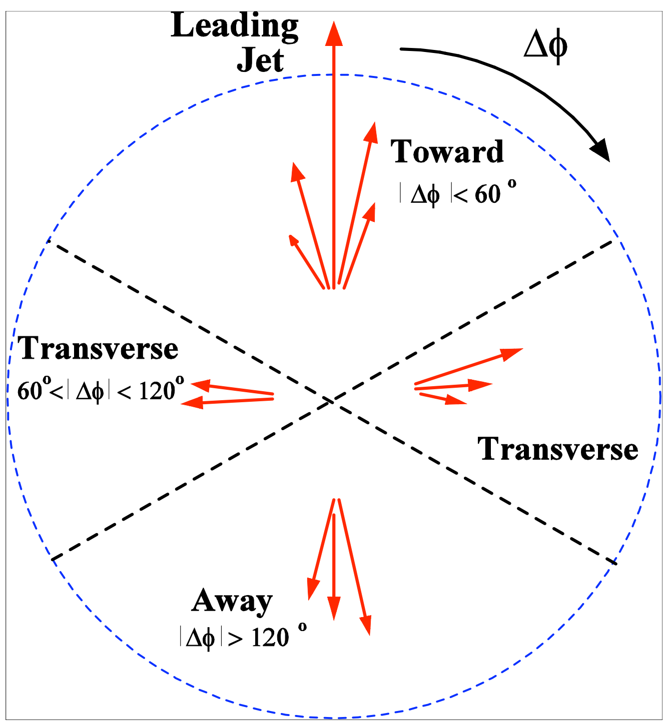
ATL-PHYS-PUB-2006-013

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

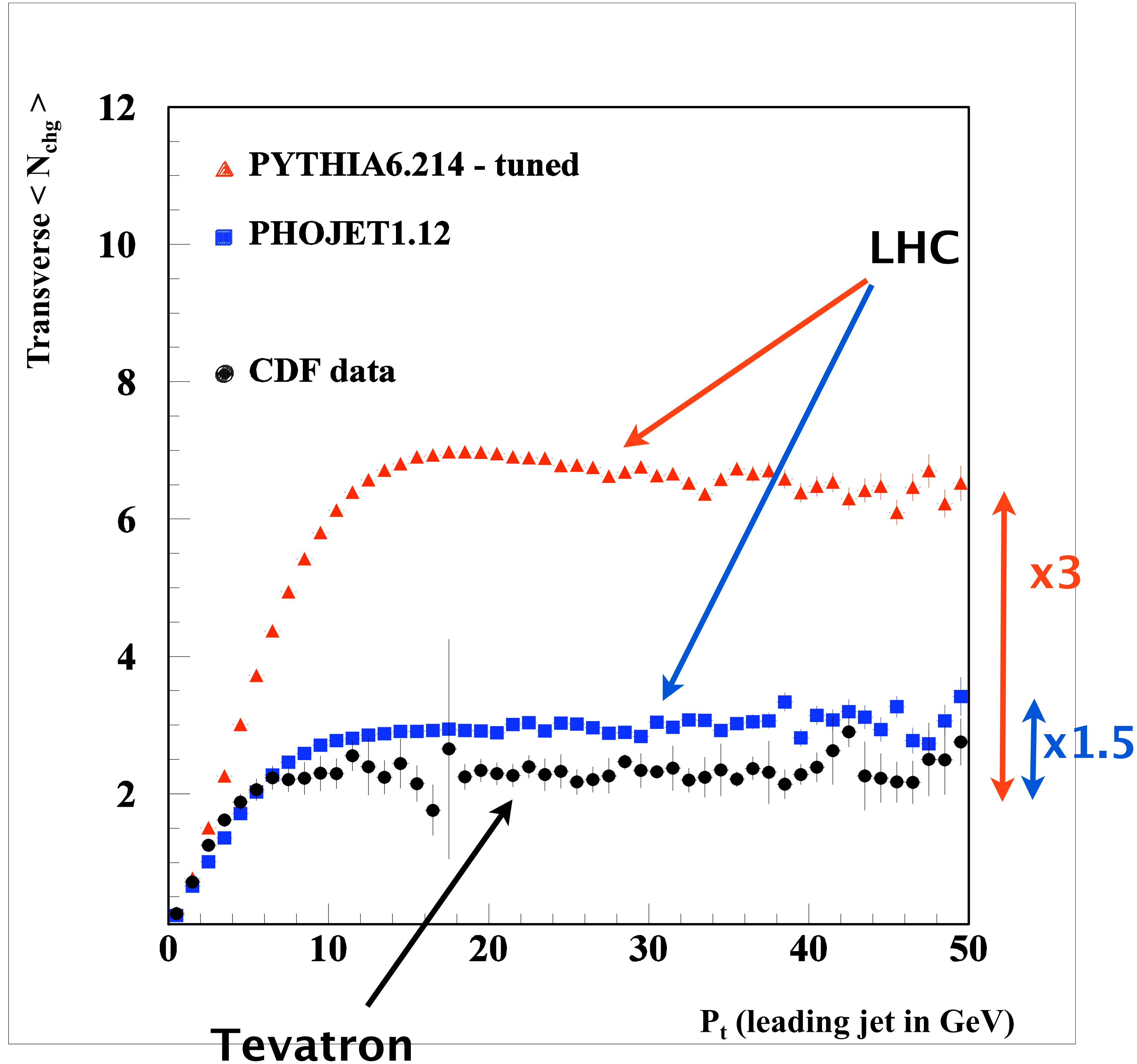
CDF - Run I "Style"

Charged particles:
$p_t > 0.5$ GeV and $|\eta| < 1$

Cone jet finder: R=0.7



UE particles come from region transverse to the leading jet.



Reconstructing the underlying event

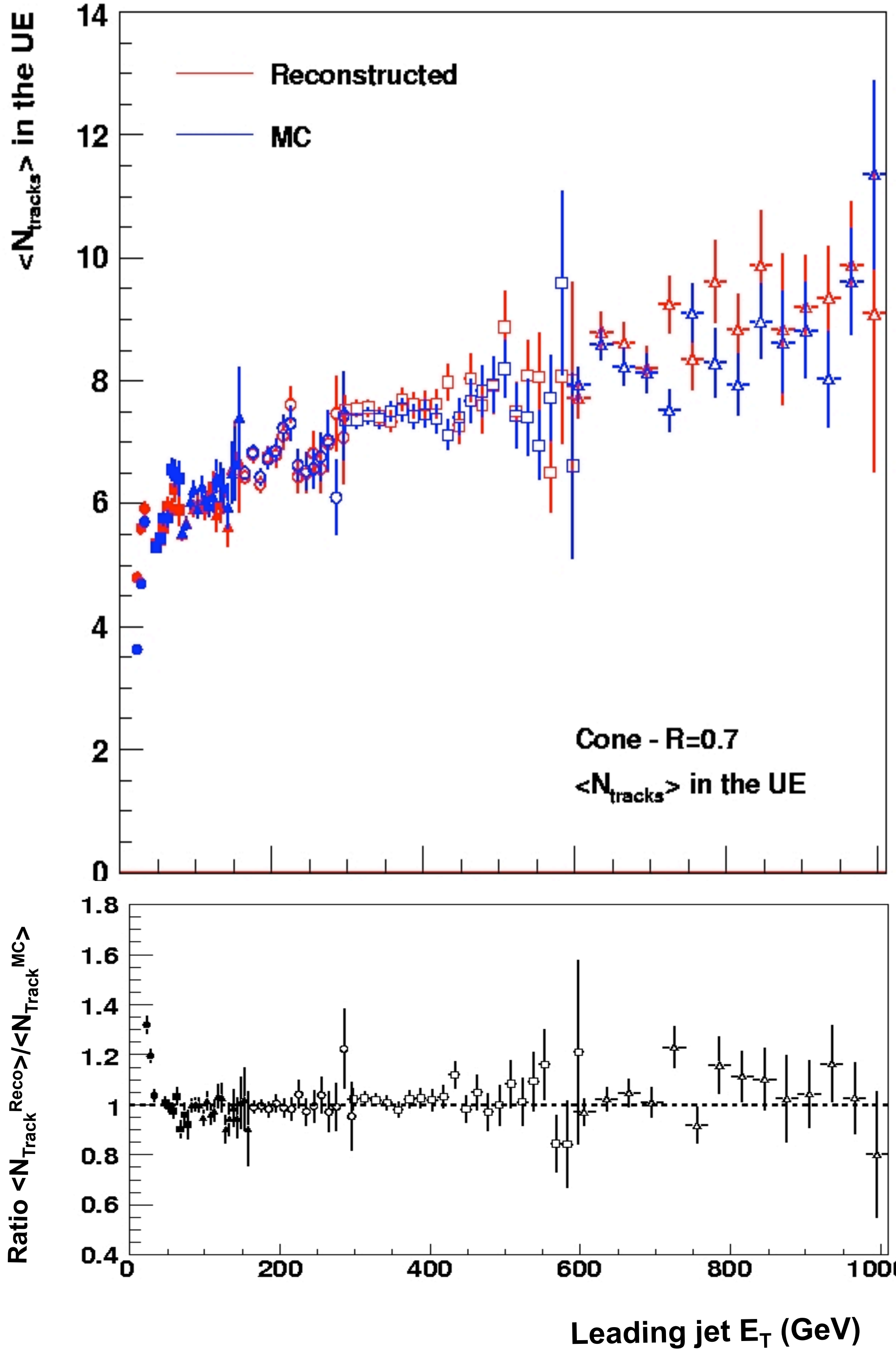
Selecting the underlying event:

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

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

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 $\bar{q}q$)	**$W^{\pm}$ 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, $W^{\pm}$-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:

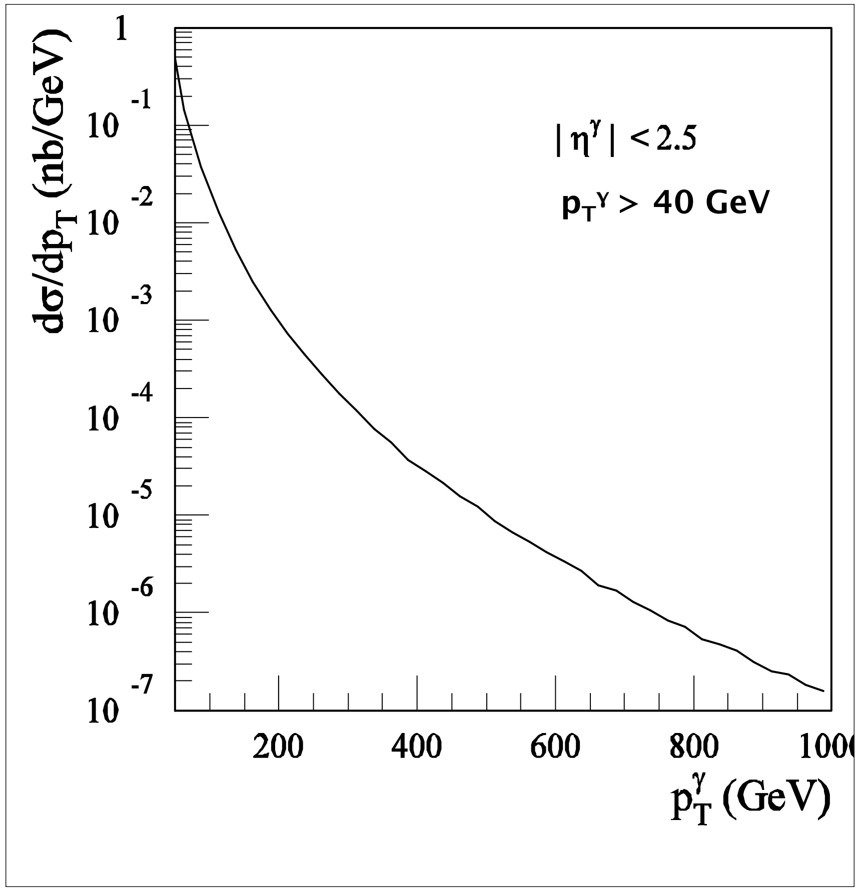
$qg \to \gamma q$	dominant (QCD Compton scattering)
$q\bar{q} \to \gamma g$	

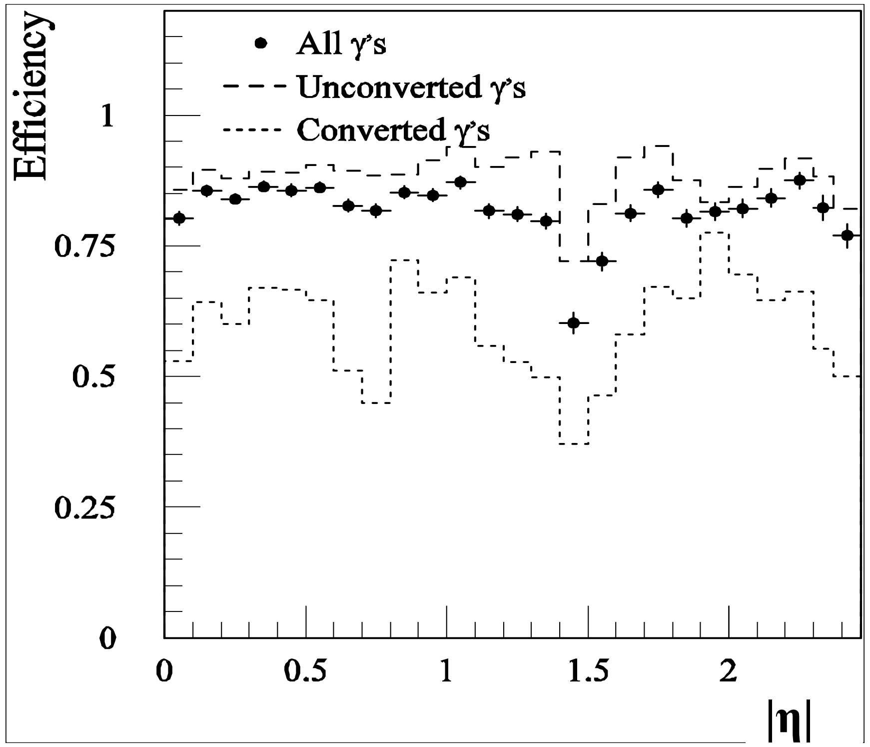
Background: mainly related to fragmentation (non-perturbative QCD)

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

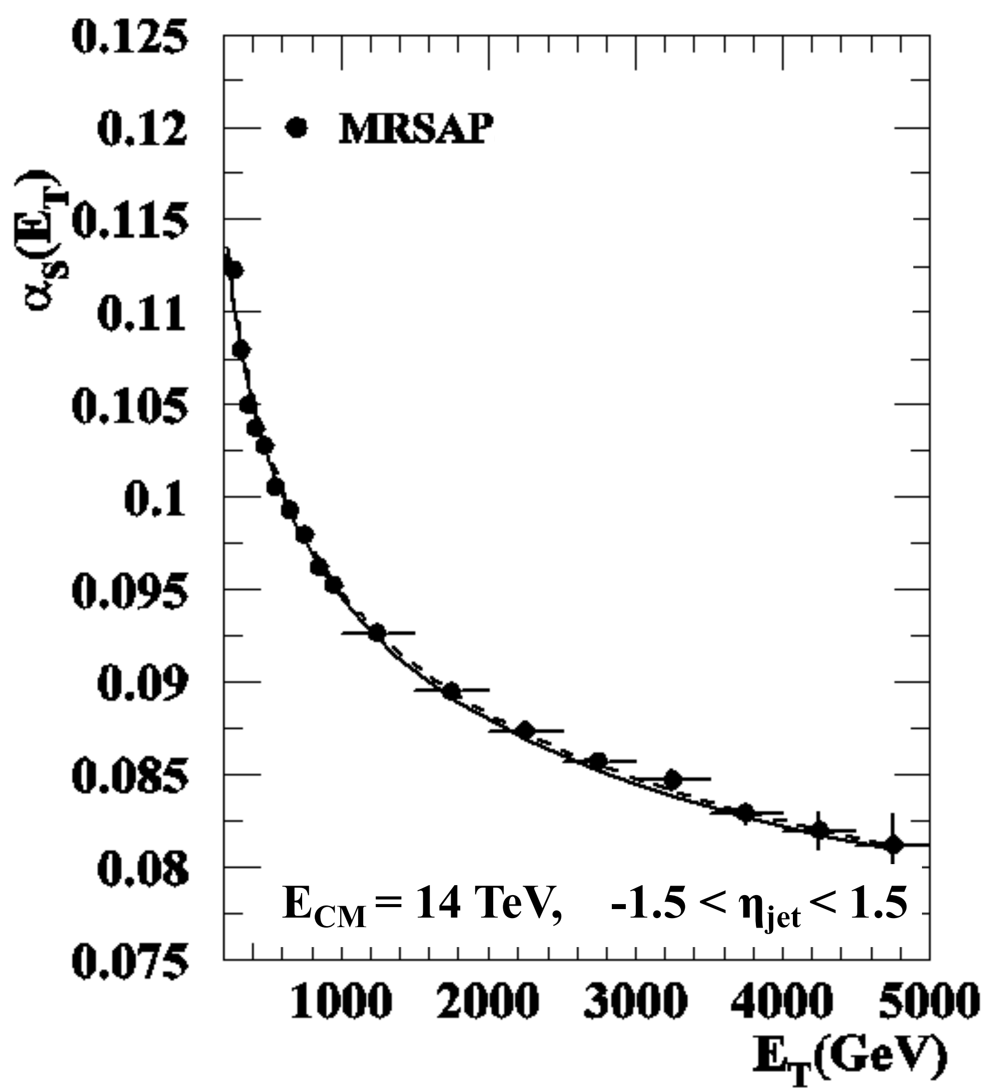
University of Glasgow

- 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)

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

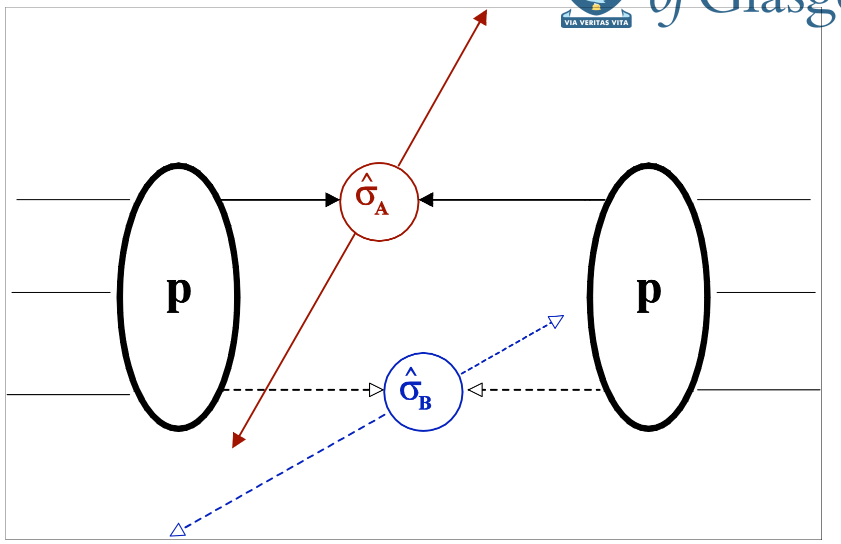


- A and B are calculated at NLO with input p.d.f.'s.

- 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



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

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

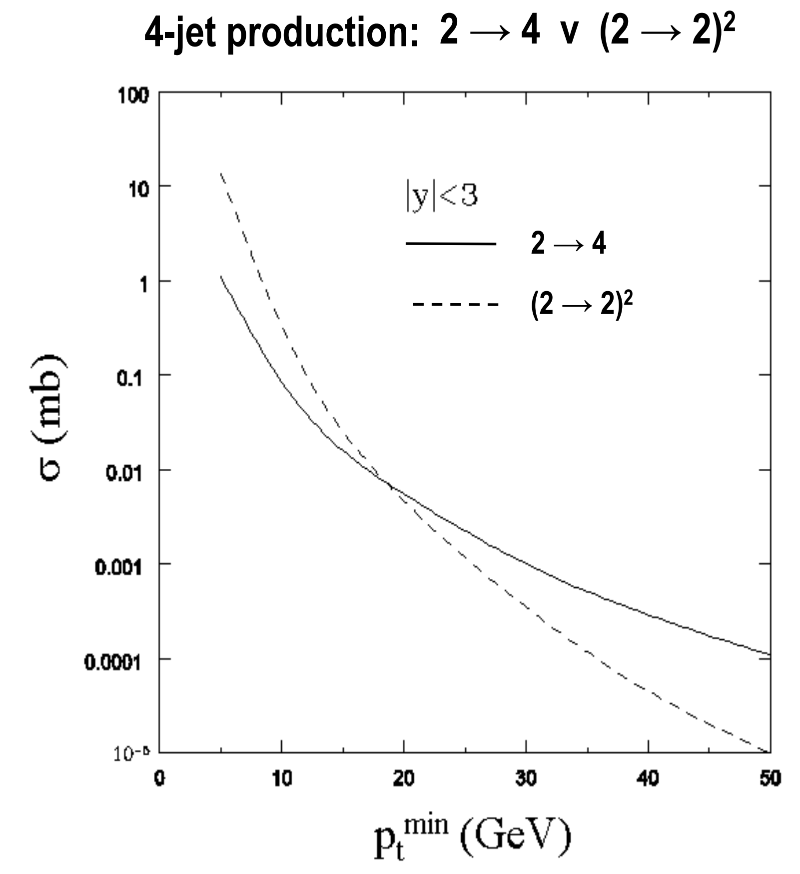
$\sigma_{eff} = 14.5 \pm 1.7$ mb

- 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,
  - $t\bar{t}$ → ll$b\bar{b}$,
  - final states with many jets p_T^{min} ~ 20 – 30 GeV.

NLO calculation priority list from Les Houches 2005: theory benchmarks

G. Heinrich and J. Huston

process ($V \in \{Z, W, \gamma\}$)	relevant for	
1. $pp \to VV$+jet	$t\bar{t}H$, new physics	*
2. $pp \to H + 2$jets	H production by vector boson fusion (VBF)	*
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$	+
4. $pp \to t\bar{t} + 2$jets	$t\bar{t}H$	
5. $pp \to VVb\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics	
6. $pp \to VV + 2$jets	VBF$\to H \to VV$	
7. $pp \to V + 3$jets	various new physics signatures	+
8. $pp \to VVV$	SUSY trilepton	*

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

*completed since list
+people are working

What about time lag in going from availability of matrix elements to having a parton level Monte Carlo available?
See e.g. H + 2 jets. Other processes are going to be just as complex.

- $pp \to$ VV + jet: One of the most promising channels for Higgs production in the low mass range is through the $H \to WW^*$ channel, with the W's decaying semi-leptonically. It is useful to look both in the $H \to WW$ exclusive channel, along with the $H \to WW$+jet channel. The calculation of $pp \to WW$+jet will be especially important in understanding the background to the latter.
- $pp \to H$+2 jets: A measurement of vector boson fusion (VBF) production of the Higgs boson will allow the determination of the Higgs coupling to vector bosons. One of the key signatures for this process is the presence of forward-backward tagging jets. Thus, QCD production of H + 2 jets must be understood, especially as the rates for the two are comparable in the kinematic regions of interest.
- $pp \to t\bar{t}b\bar{b}$ and $pp \to t\bar{t}$ + 2 jets: Both of these processes serve as background to $t\bar{t}H$, where the Higgs decays into a $b\bar{b}$ pair. The rate for $t\bar{t}jj$ is much greater than that for $t\bar{t}b\bar{b}$ and thus, even if 3 b-tags are required, there may be a significant chance for the heavy flavour mistag of a $t\bar{t}jj$ event to contribute to the background.
- $pp \to VVb\bar{b}$: Such a signature serves as non-resonant background to $t\bar{t}$ production as well as to possible new physics.
- $pp \to$ VV + 2 jets: The process serves as a background to VBF production of Higgs.
- $pp \to$ V + 3 jets: The process serves as background for $t\bar{t}$ production where one of the jets may not be reconstructed, as well as for various new physics signatures involving leptons, jets and missing transverse momentum.
- $pp \to VVV$: The process serves as a background for various new physics subprocesses such as SUSY tri-lepton production.

Summary:

- LHC will probe QCD to unexplored kinematic limits;
- Minimum-bias and the underlying event: improved understanding of events dominated by soft processes.
- 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 ($H\rightarrow\gamma\gamma$), $f_g(x)$ 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;