Minimum bias and early QCD physics at LHC

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(on behalf of the ATLAS and CMS collaborations)

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PHYSICS AT THE TERA SCALE
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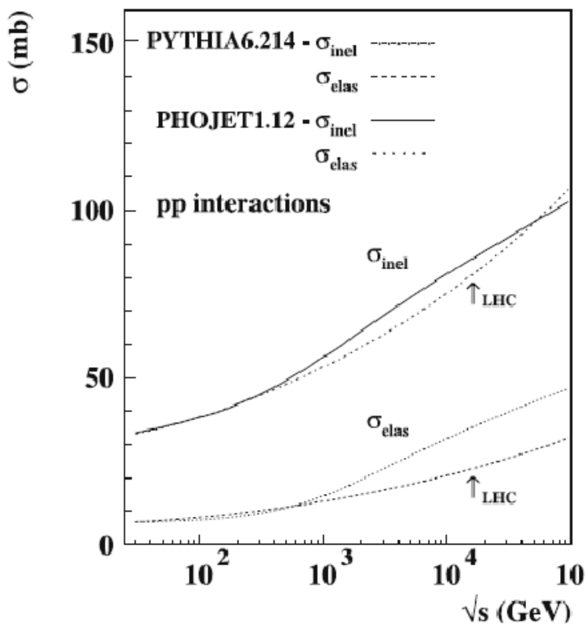
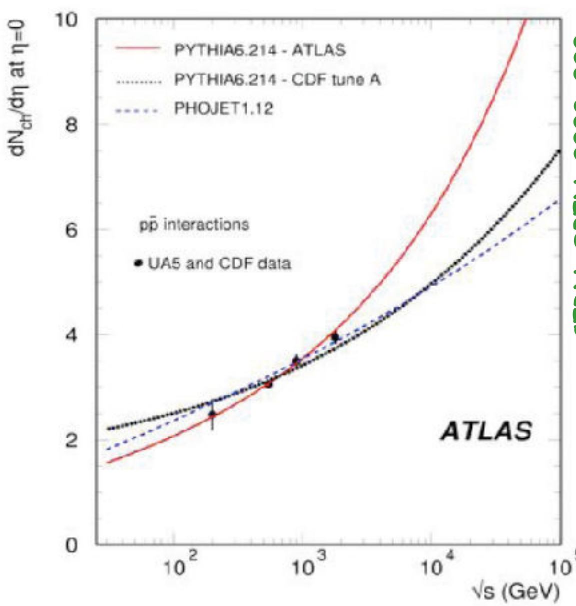
Motivation

- with the LHC we will enter soon a new kinematic regime
  - → that is what it has been built for … (search for new physics)
- perturbative QCD is the well tested theory of the strong interaction
  - → non-perturbative effects mostly treated in phenomenological approaches
    - e.g. models tuned to existing data and extrapolated to higher energies
- need to perform 'basic' measurements on properties of pp collisions
  - → validate our understanding of backgrounds for new physics measurements
    - based today still on Monte Carlo models



Eur.Phys.J. C50 435-466 (2007)



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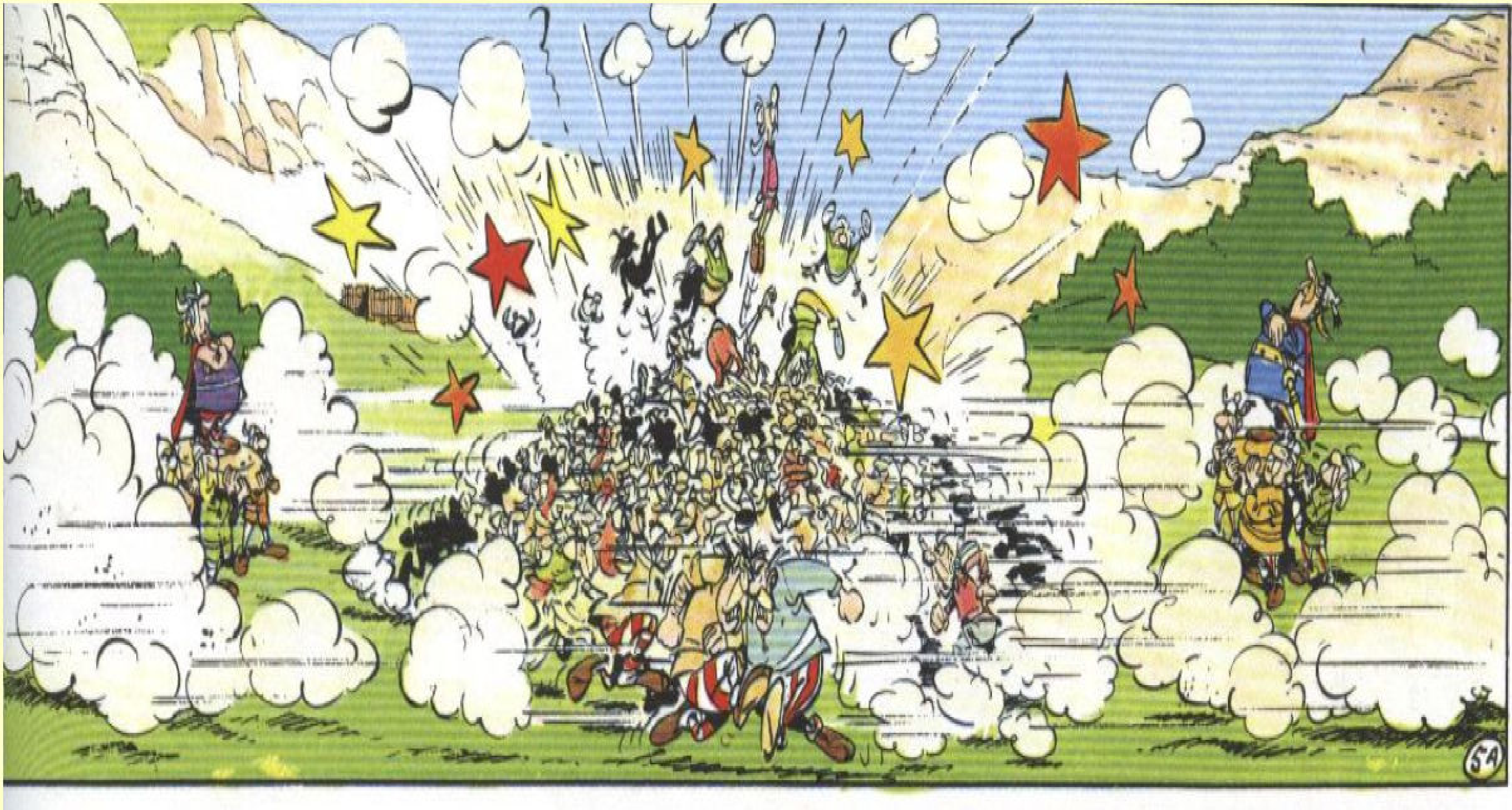
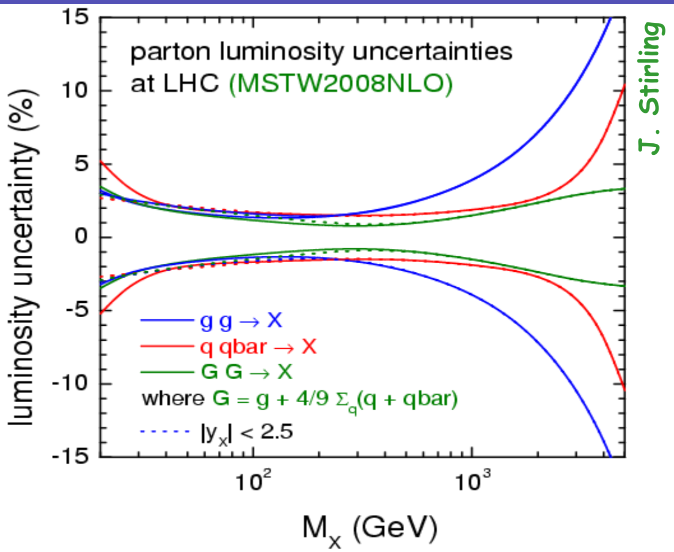
The complexity of pp at LHC



- Pile-up included or not yet ?

Schema of pp collision

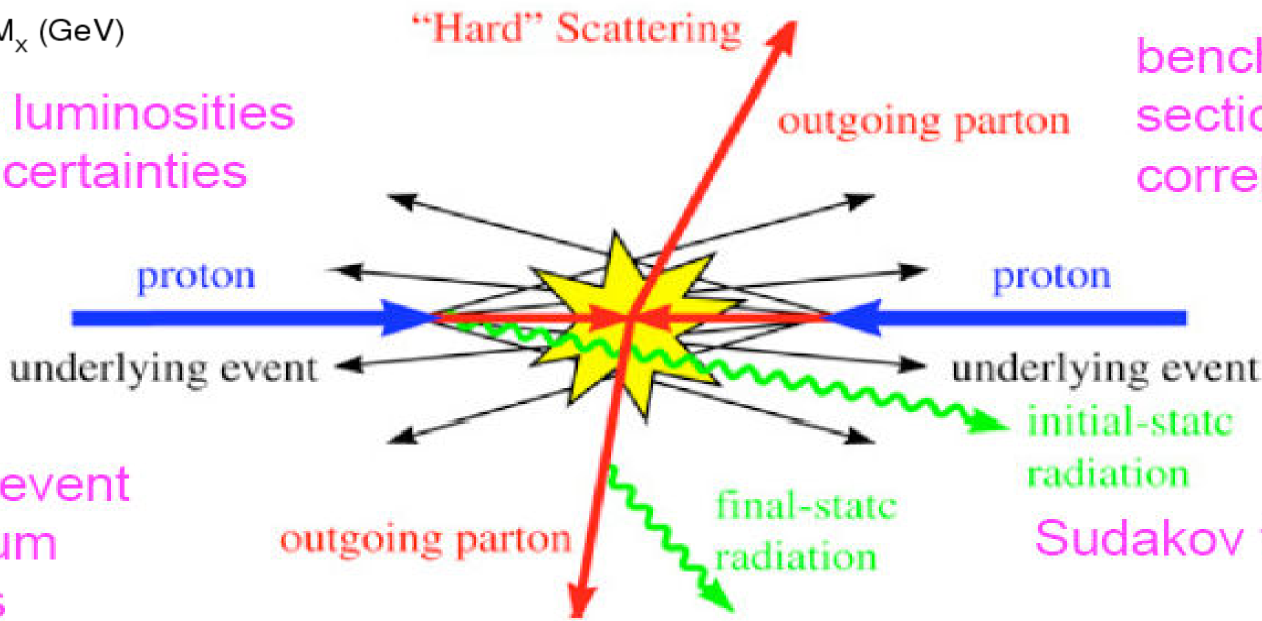


- interesting part: the hard scatter
  - → but it does not come alone

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations



underlying event and minimum bias events

Sudakov form factors

jet algorithms and jet reconstruction

R. Field, Acta Phys. Pol. B39 (2008) Vol. 10, 2611

LHC &
ATLAS and CMS

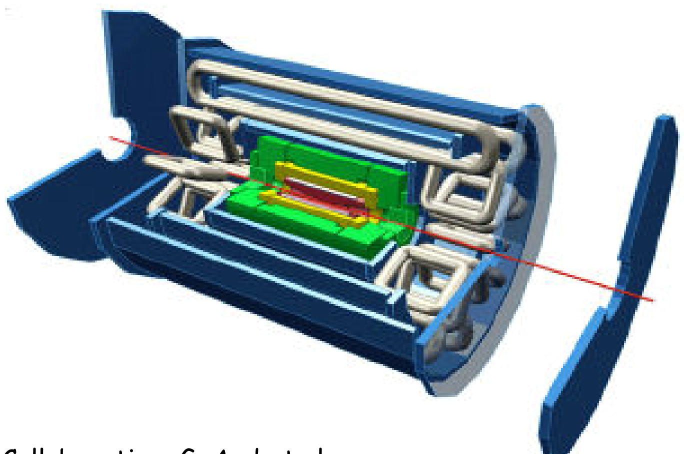
LHC: expectation for 2009/2010

- initial collisions in 2009
  at injection energy → $\sqrt{s}$ = 900 GeV
  → instantaneous luminosity up to $2*10^{28}\ cm^{-2}\ s^{-1}$
  → integrated luminosity up to 1 nb^{-1}/24 h

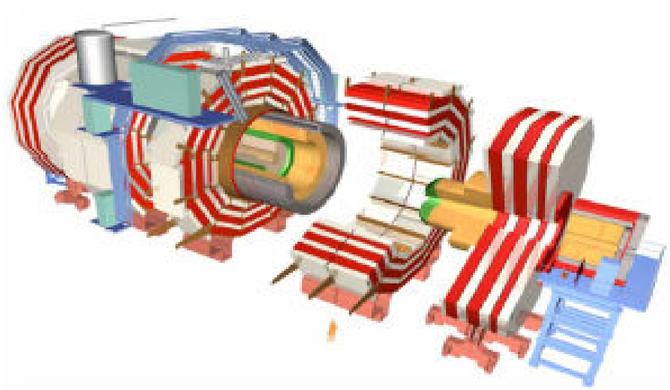
- high energy run starting with $\sqrt{s}$ = 7 TeV
  → possible ramp-up during 2010 to $\sqrt{s}$ = 8-10 TeV
  → instantaneous luminosity up to $1\text{-}2*10^{32}\ cm^{-2}\ s^{-1}$
    - Note: up to (on average) 2 inelastic interactions per bunch crossing possible ('pile-up')
  → integrated luminosity up to 200-300 pb^{-1}
    - possibly shared between two c.m.s. energies

ATLAS and CMS

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\mathrm{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\mathrm{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass+scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID +MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (DT/CSC+Tracker)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)



The ATLAS Collaboration, G. Aad et al.,
The ATLAS Experiment at the CERN Large Hadron Collider,
JINST 3 (2008) S08003.

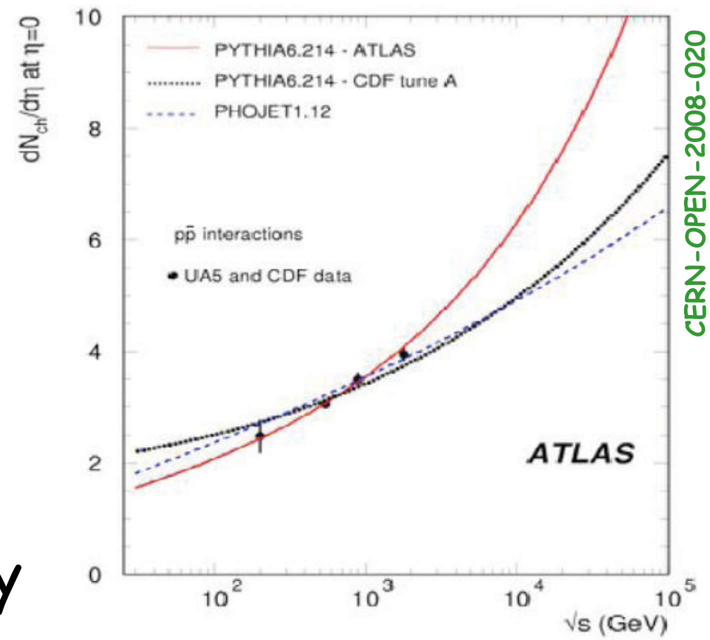


The CMS Collaboration, S. Chatrchyan et al.,
The CMS Experiment at the CERN Large Hadron Collider,
JINST 3 (2008) S08004.

Minimum bias

Minimum bias physics

- motivation
  - → basic properties of inelastic events uncertain at LHC energies
    - extrapolation from Tevatron and lower energy measurements
  - → need to understand precisely as these will be background due to pile-up at higher luminosity



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- definition of minimum bias events
  - → driven by trigger and experimental selection
    - traditionally: non-single diffractive inelastic events (NSD)
    - backgrounds due to
      - ➔ beam-gas and beam-halo events
      - ➔ pile-up events

$$\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \underbrace{\sigma_{dd} + \sigma_{nd}}_{\text{NSD}}$$

Minimum bias measurements (historical)

C. Amsler et al., Phys. Lett. B667, 1 (2008) 20

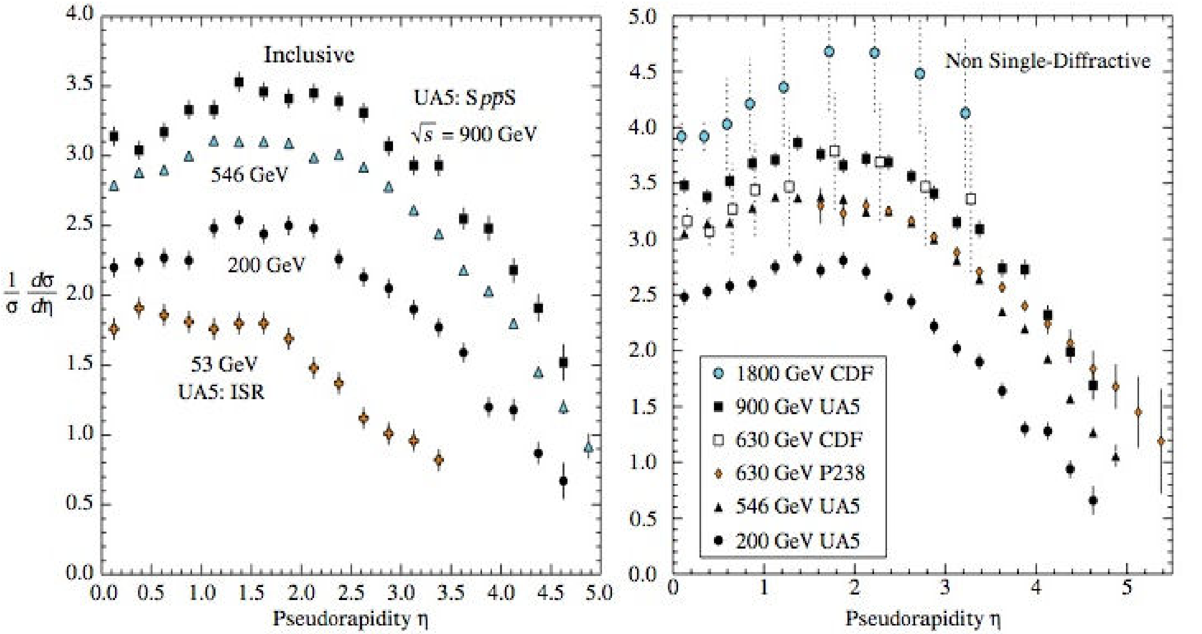


Figure 40.4: Charged particle pseudorapidity distributions in $p\bar{p}$ collisions for 53 GeV $\leq \sqrt{s} \leq$ 1800 GeV. UA5 data from the $Sp\bar{p}S$ are taken from G.J. Alner *et al.*, Z. Phys. **C33**, 1 (1986), and from the ISR from K. Alpgøard *et al.*, Phys. Lett. **112B**, 193 (1982). The UA5 data are shown for both the full inelastic cross section and with singly diffractive events excluded. Additional non single-diffractive measurements are available from CDF at the Tevatron, F. Abe *et al.*, Phys. Rev. **D41**, 2330 (1990) and Experiment P238 at the $Sp\bar{p}S$, R. Harr *et al.*, Phys. Lett. **B401**, 176 (1997). (Courtesy of D.R. Ward, Cambridge Univ., 1999)

F. Abe, et al., Phys. Rev. Lett. 61, 1819 (1988)

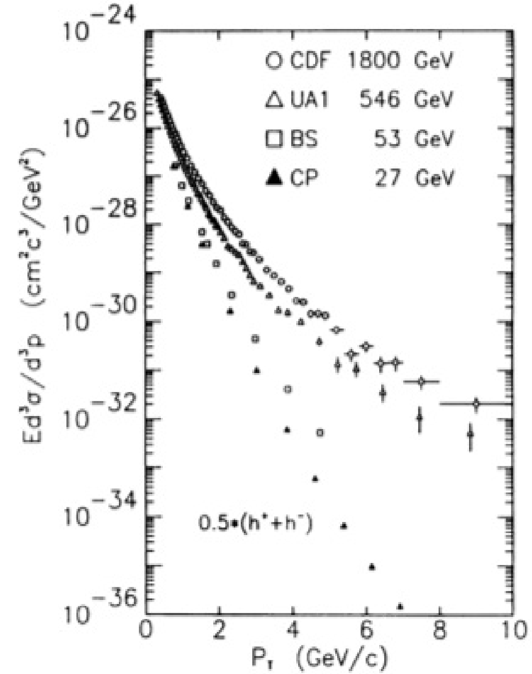
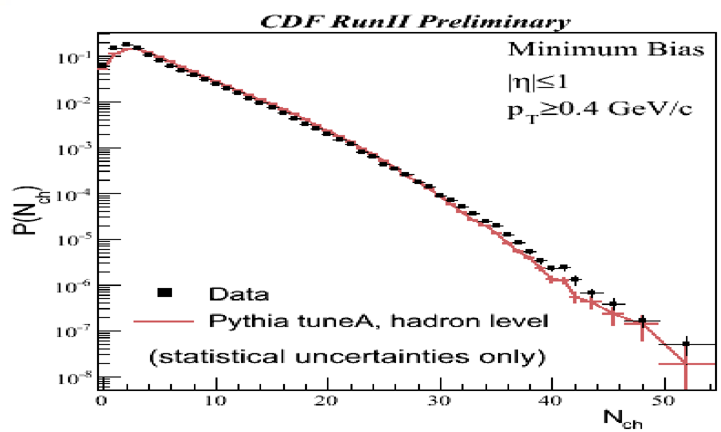
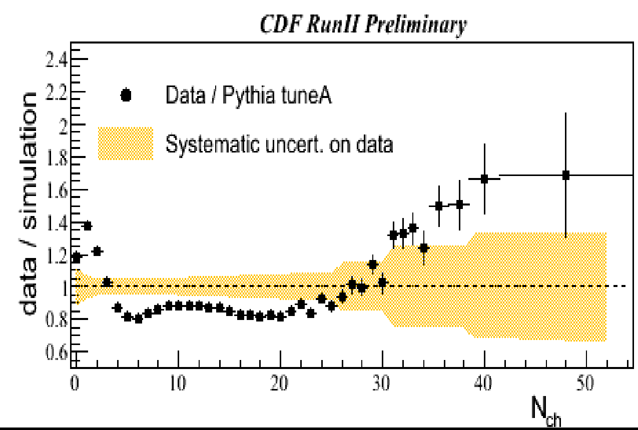


FIG. 3. Energy dependence of inclusive cross sections. Chicago-Princeton (CP) ($y = 0$) Ref. 2, British-Scandanavian (BS) ($y = 0$) Ref. 3, UA1 ($|y| < 2.5$) Ref. 7, and CDF ($|y| < 1.0$) collaborations.

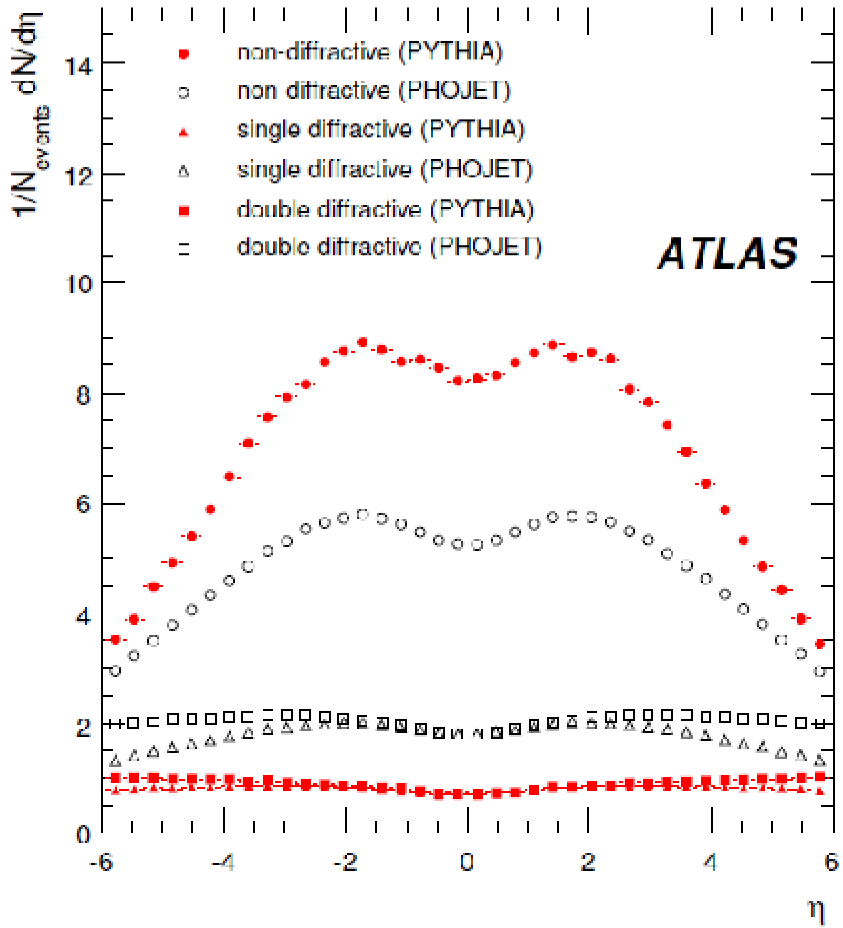
- only a small fraction shown …

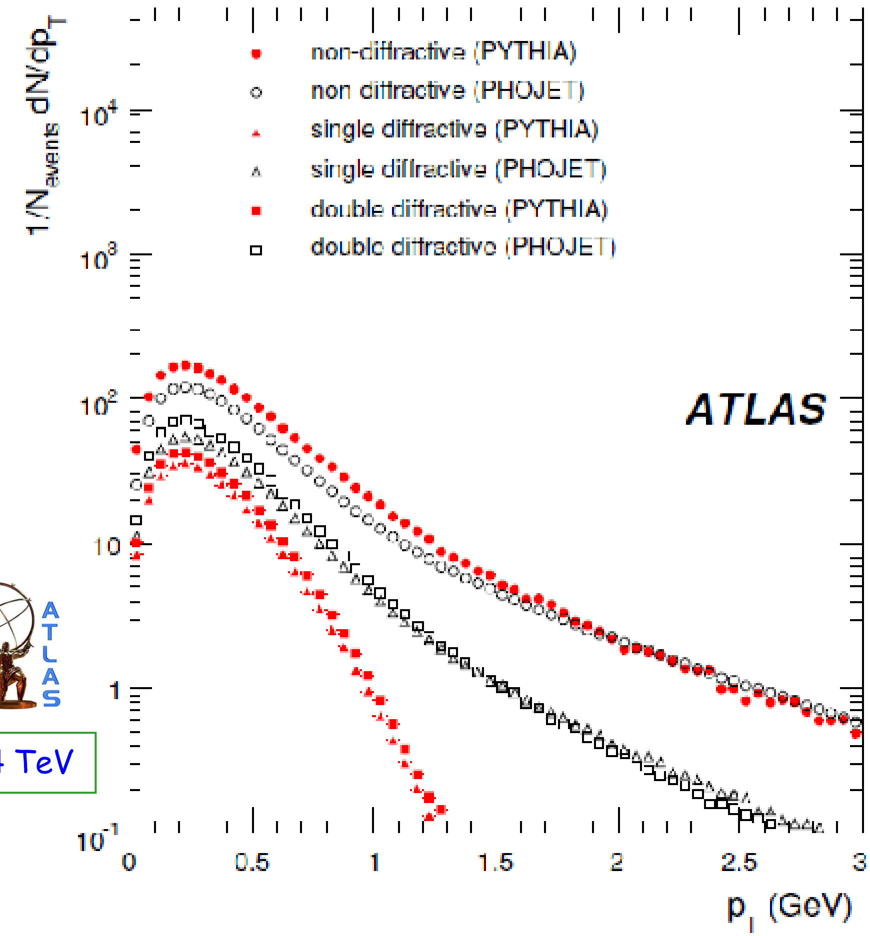




CDF Collaboration, Public CDF note 9936

LHC expectation





$\sqrt{s}$=14 TeV

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- sizeable differences in the prediction
  → absolute magnitude as well as shape

Minimum bias measurement techniques

- trigger selection
  - → random trigger (L1)
    - zero bias
    - inefficient for low L
  - → random trigger (L1) and track selection (HLT)
    - enhance efficiency for low luminosity
  - → dedicated trigger scintillators (ATLAS)
    - not zero bias
  - → forward calorimeters (CMS)
    - not zero bias

- observables
  - based on charged particle reconstruction
  - → charged particle multiplicity
    - h dependence
  - → charge particle p_T spectrum
  - → average charge particle p_T vs. η

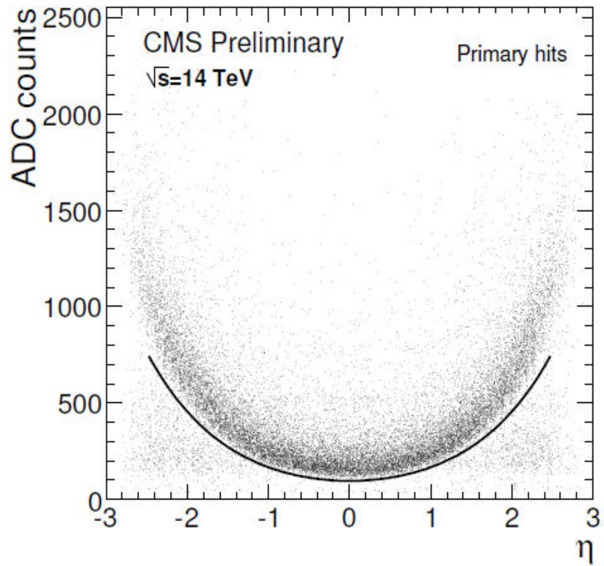
- neutral particles to be studied with calorimetric measurements
  - not discussed here

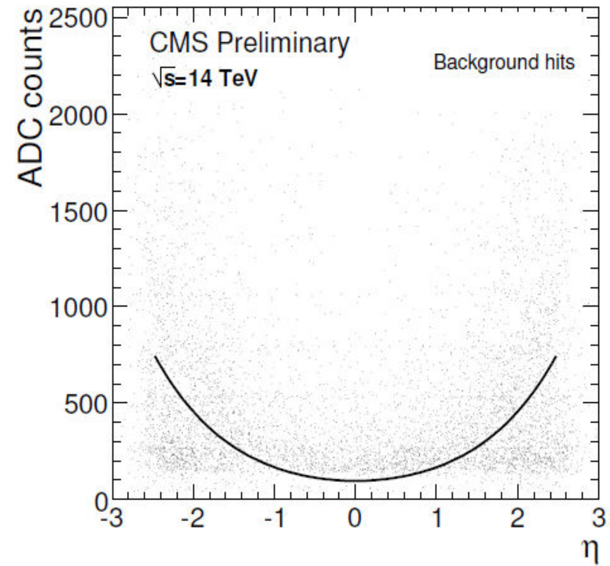
Minimum bias measurements

- charged particle reconstruction
  - various possibilities with different systematics
  - → hit counting
    - estimate charged particle density via number of hits (clusters) in pixel detector layer(s)
      - ➔ pros: access to low p_T particles
      - ➔ cons: determine secondary contribution from MC, no momentum measurement
  - → "tracklets"
    - correlate hits in two (three) detector layers to form track candidates
      - ➔ pros: access to lower p_T particles
      - ➔ cons: no momentum measurement
  - → tracks
    - reconstruct complete tracks
      - ➔ pros: low fake rate, momentum measurement
      - ➔ cons: challenge to access low p_T region
- vertexing: important tool to remove fakes and background
  - → and identify if several interactions per bunch crossing

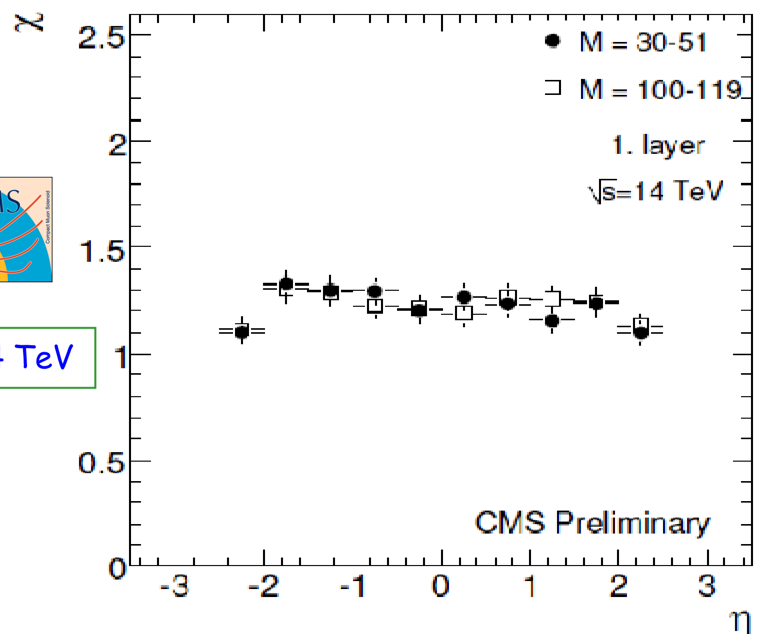
Minimum bias: hit counting

- method: count hits in pixel layer(s)
  - → innermost pixel layer reached for p_T>30 MeV
- event selection
  - → zero bias trigger
  - → reconstructed vertex (η calculation)
    - otherwise assume nominal position
- hit selection
  - → cut on energy deposition





√s=14 TeV

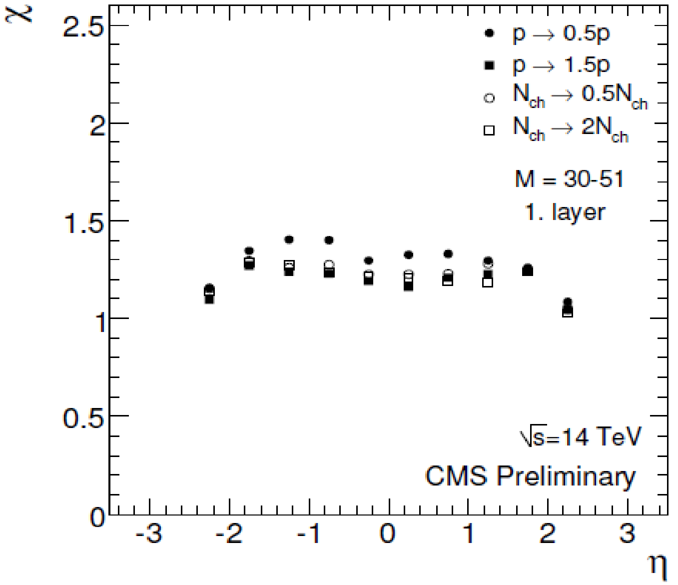


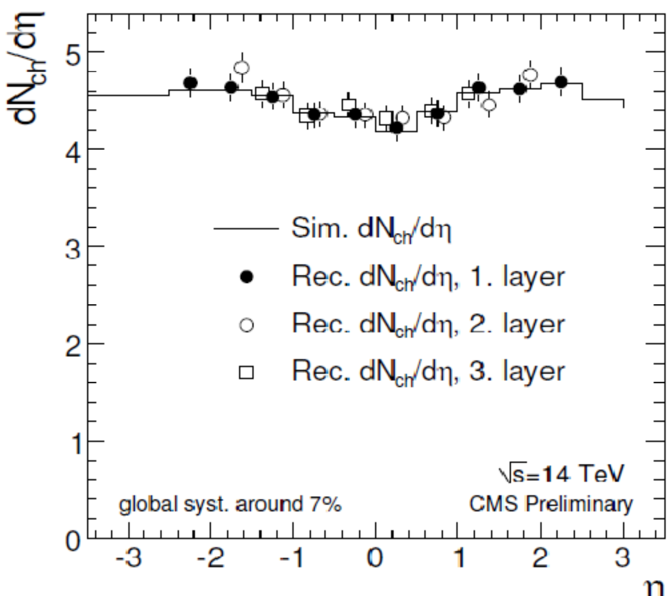
CMS-PAS-QCD-08-004

- correction for
  - → event selection
  - → loopers
  - → hit to track:

$$\chi(\eta, M) = \frac{H^{MC}(\eta, M)}{T^{MC}(\eta, M)}$$

Minimum bias: hit counting

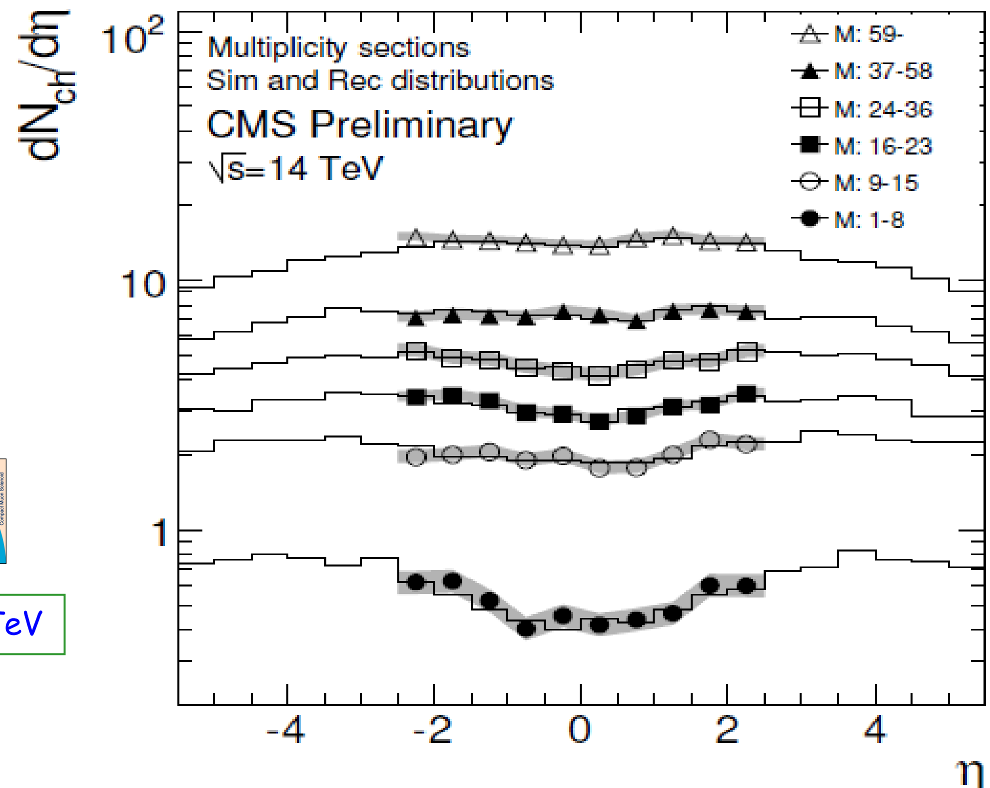




- systematic uncertainties due to
  - → vertex efficiency
  - → vertex bias
  - → model dependence of correction

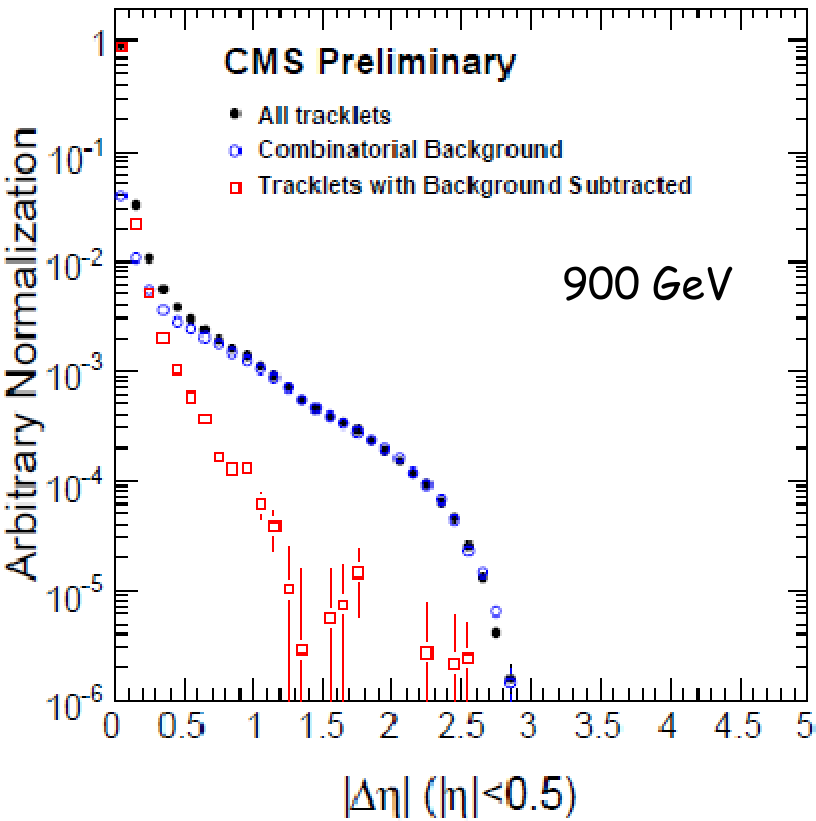
CMS-PAS-QCD-08-004

√s=14 TeV



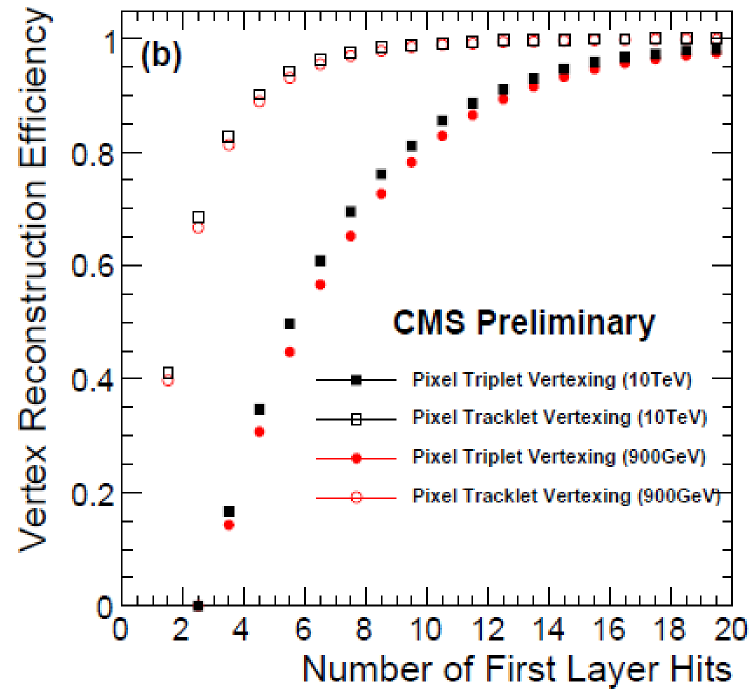
Minimum bias: tracklets

- tracklet: pair of hits in first two pixel layers
  - → determine event vertex based on tracklets



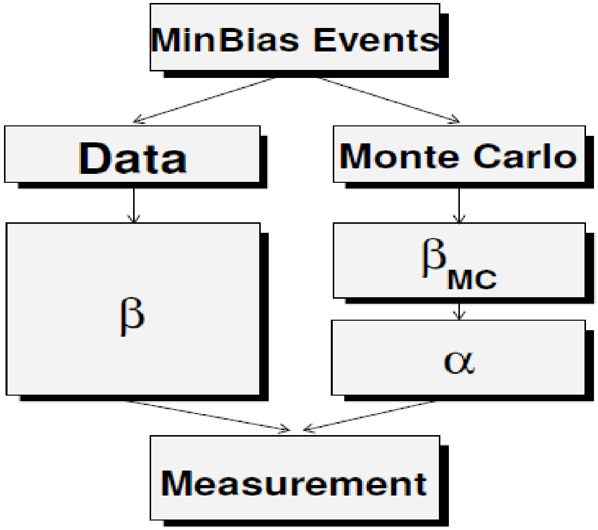
CMS-PAS-QCD-09-002

√s=900 GeV (10 TeV)



- event selection
  - → zero bias trigger
  - → reconstructed vertex
- background subtraction
  - → from data based on sidebands

Minimum bias: tracklets

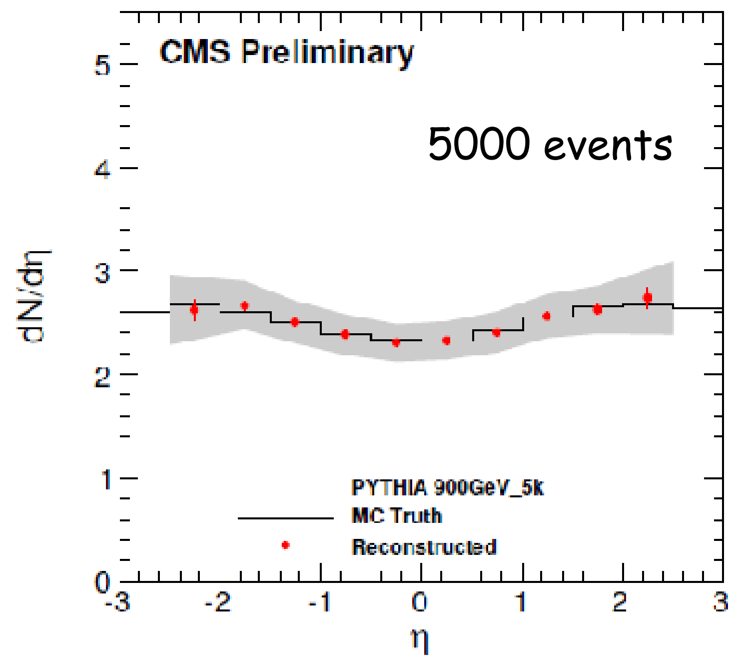


CMS-PAS-QCD-09-002

Source	Related correction factor	900GeV (%)	10TeV (%)
Statistical error of α	α	1.0	1.0
Monte Carlo efficiency correction	α	0.5-2.0	0.5-2.5
Pixel hit reconstruction algorithm	α	0.1	0.1
Pixel hit reconstruction efficiency	α	5.0	5.5
Pixel hit splitting	α	1.5-3.5	1.0-2.0
Acceptance uncertainty	α	0.0-10.0	0.0-10.0
Background subtraction	β	0.5-1.5	0.5-2.0
Misalignment	α, β	1.0	2.0
Random hits from beam halo and loopers	α, β	0.1-1.5	0.1-1.0
GEANT Simulation	α, β	2.0	2.0
Effect of event pile-up	α, β	1.0	1.0
Correction on event selection	ξ	5.0	5.0
Total		7.5-13.5	8.5-13.5

$\sqrt{s}$=900 GeV
(10 TeV)

- procedure
  - → correction factor α
    - from MC
  - → background fraction β
    - from 'data'
  - → event selection correction ξ
    - from MC: range 0.83 - 0.87



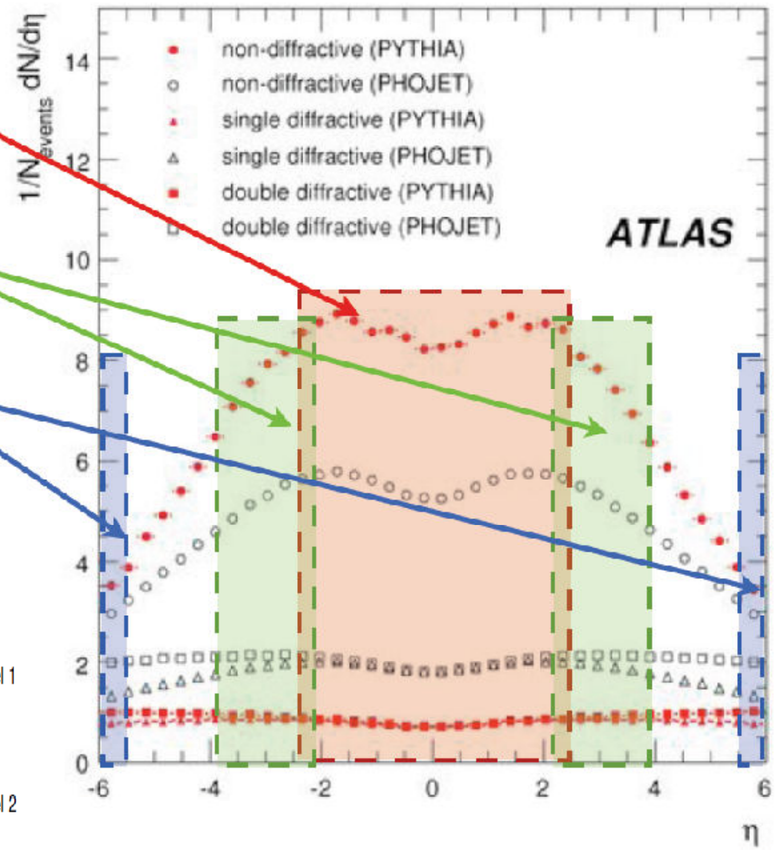
Trigger for minimum bias

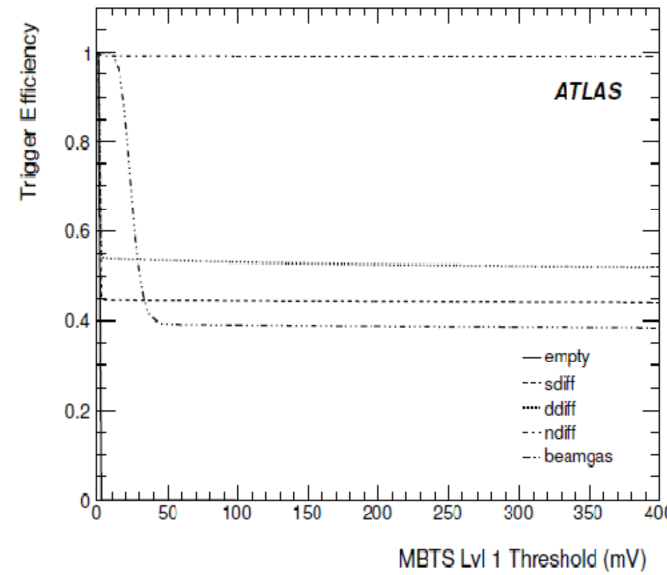
Inner detector space points

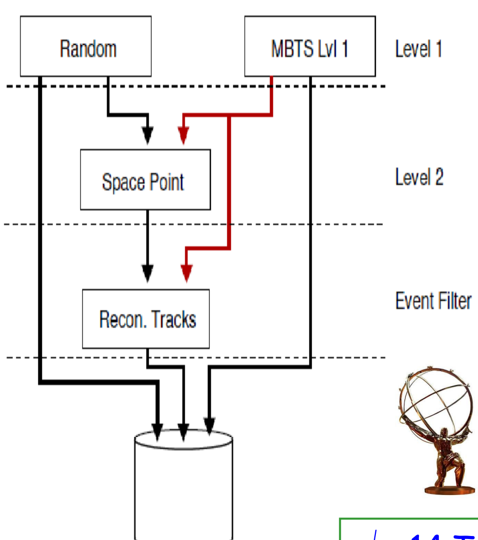
Minimum bias trigger scintillators

Cerenkov detector (LUCID)

Zero degree calorimeter (ZDC)
8.3 → ∞

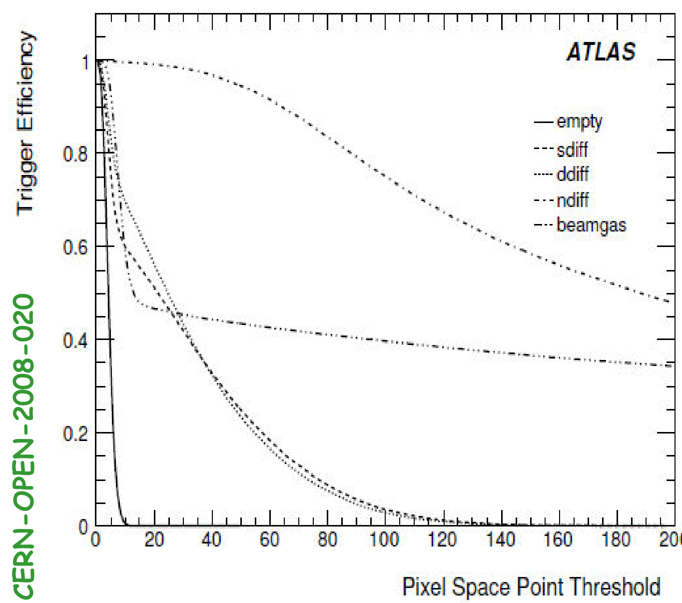






√s=14 TeV

- efficient triggers for non-diffractive inelastic events



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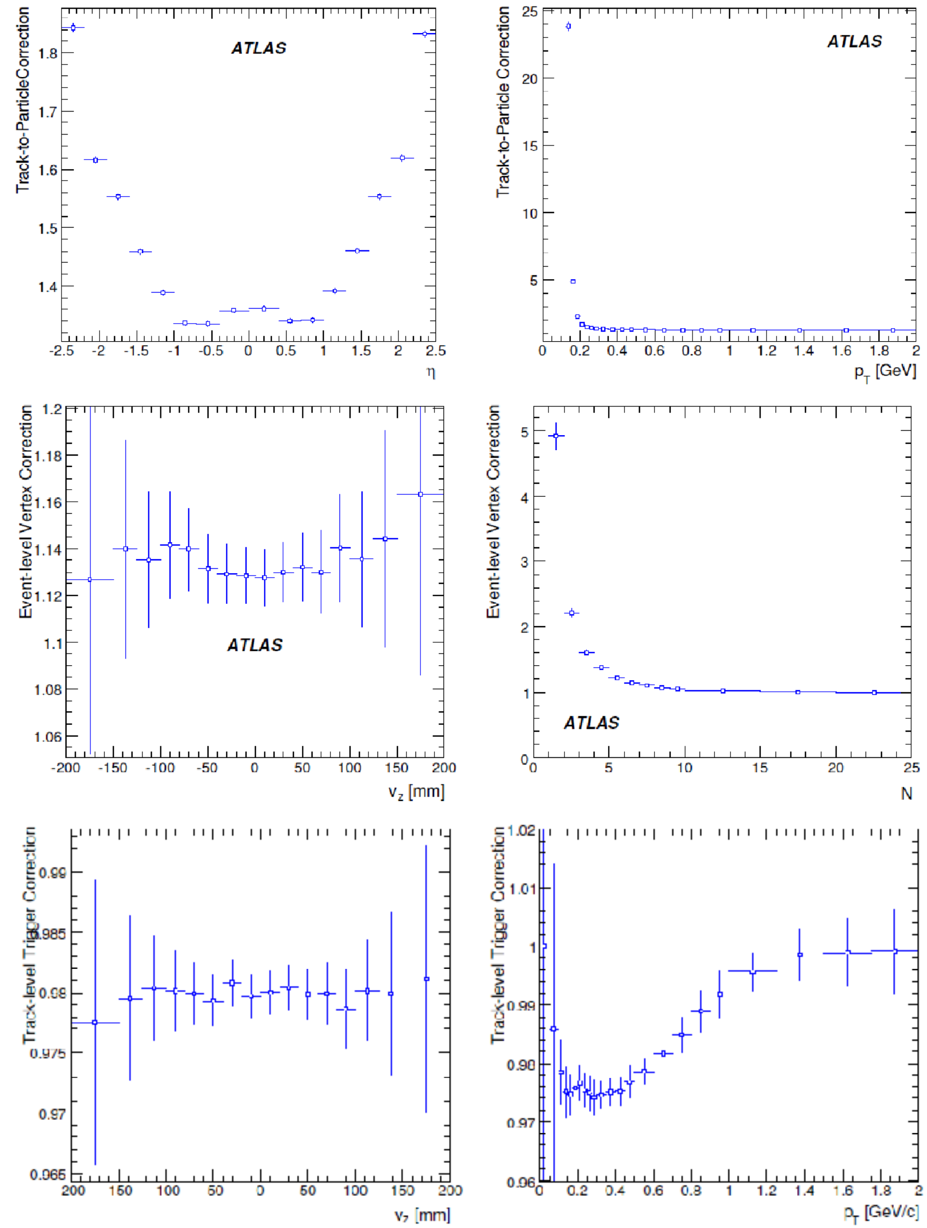
Minimum bias: particle tracks

- event selection
  - → minimum bias trigger
  - → ≥1 reconstructed vertex
  - → well reconstructed tracks with p_T> 150 MeV

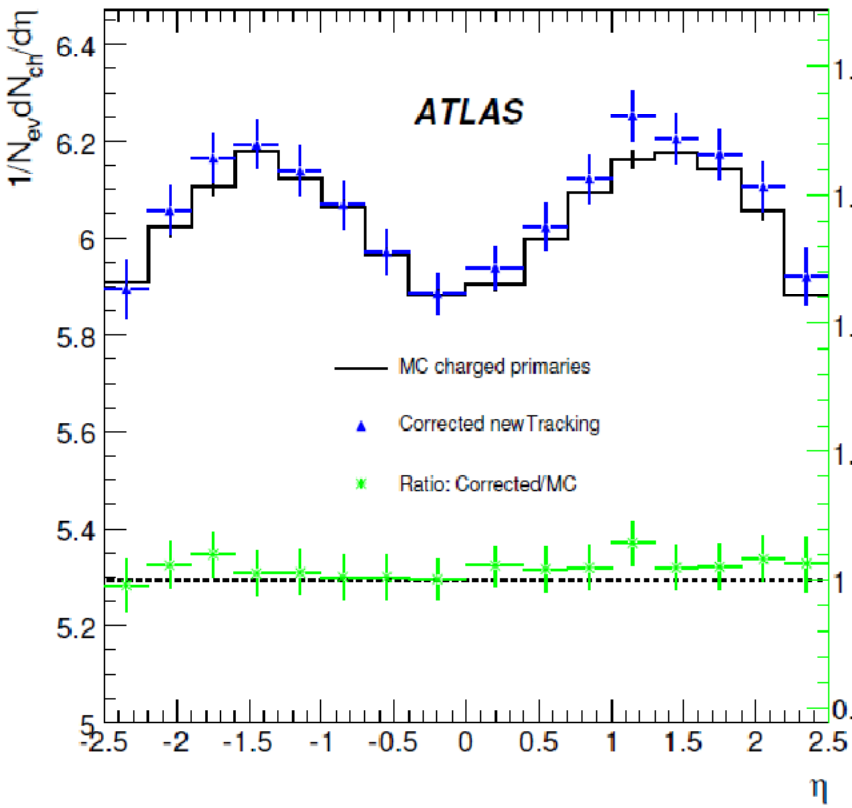
- necessary corrections
  - → track to particle
  - → vertex reconstruction
    - on event level
    - on track level
  - → trigger bias
    - on event level
    - on track level

√s=14 TeV

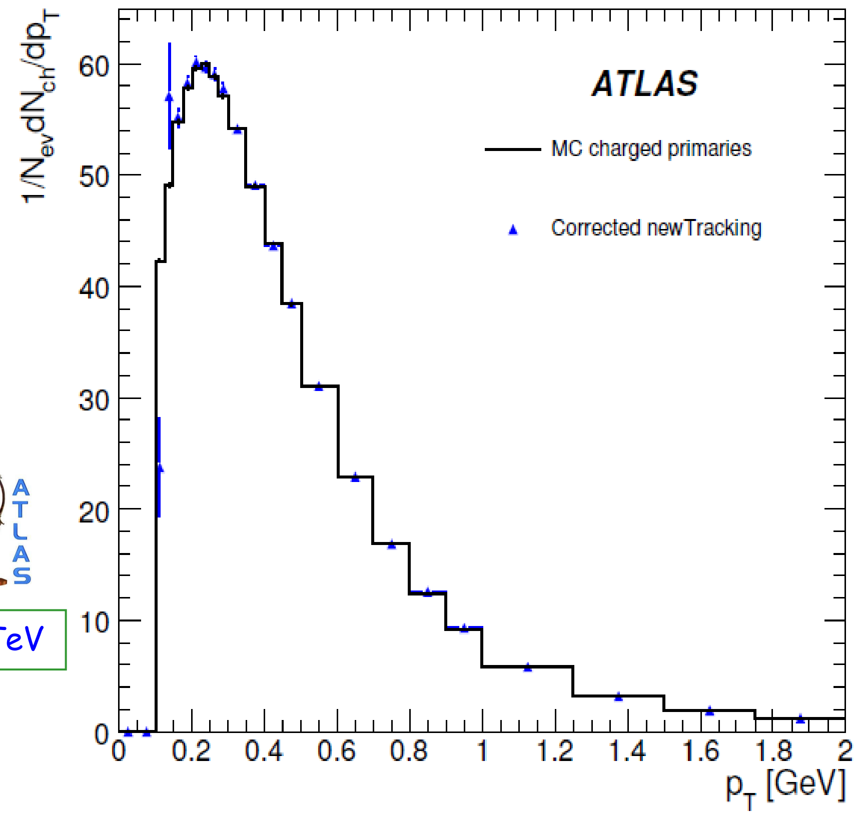
CERN-OPEN-2008-020



Minimum bias: particle tracks



√s=14 TeV



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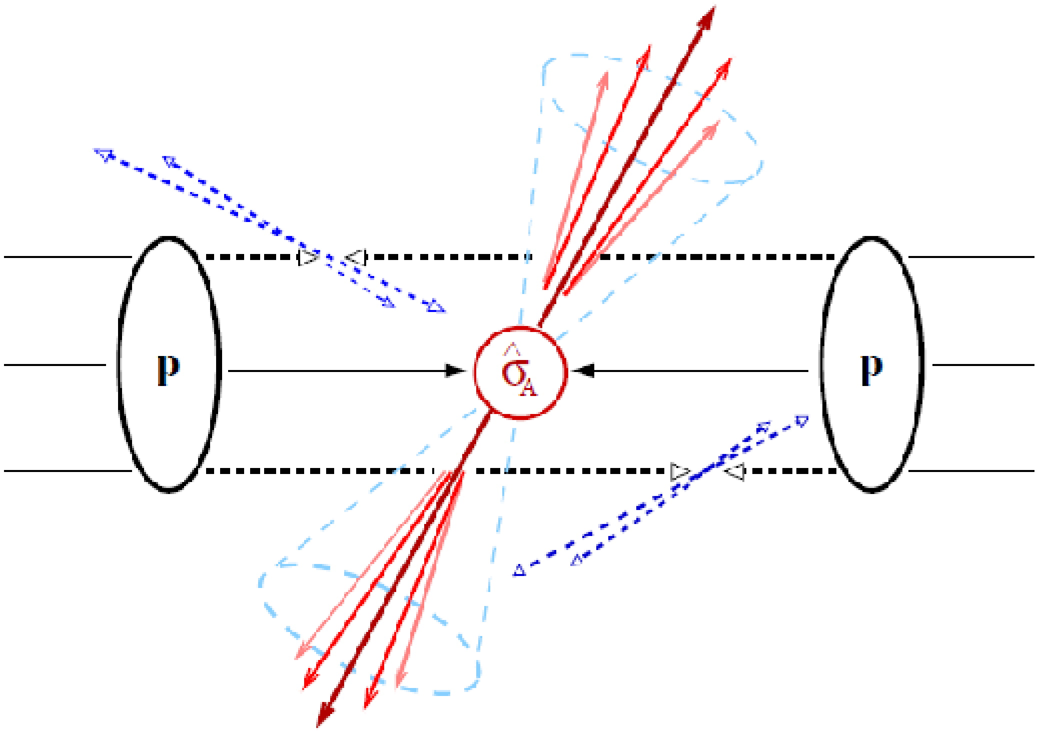
- systematic uncertainties
  - → study assumed worse misalignment
    - than presently known due to alignment based on cosmic muon data

Name	Level	Estimated Uncertainty
Track selection cuts	Analysis	2%
Mis-estimate of secondaries	Analysis	1.5%
Vertex reconstruction bias	Reconstruction	0.1%
Misalignment	Reconstruction	6%
Beam-gas and pileup	Offline Trigger	1%
Particle composition	Generation/Simulation	2%
Diffractive cross sections (NSD sample)	Generation	4%
Total		8%

Underlying event

Underlying event physics

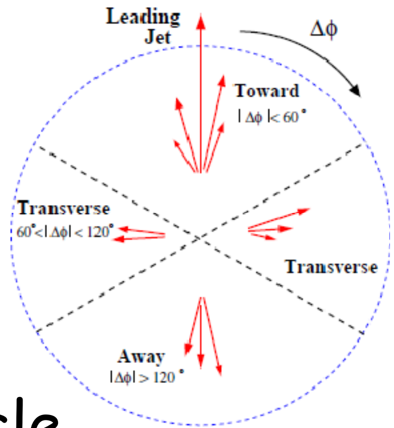
- definition
  - → everything except the hard scattering of interest
- phenomenology
  - → multiple parton interactions
  - → radiation
  - → parton distribution functions

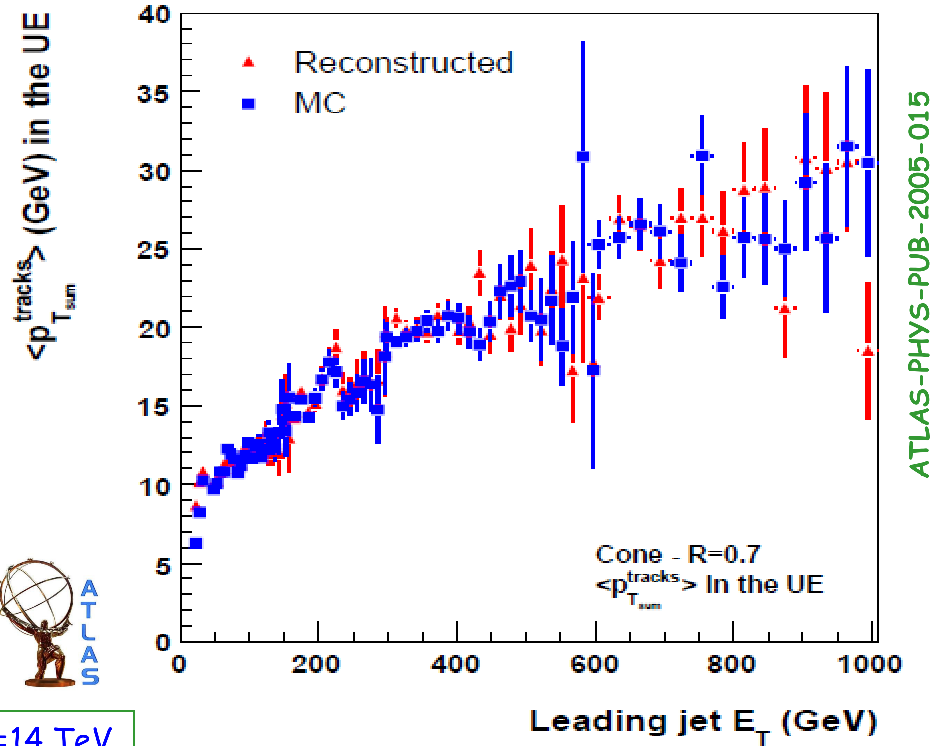


- broad program of measurements
  - → UE properties in variety of hard scattering processes
    - jet production, Drell-Yan lepton pair production, W/Z+jet production, ...

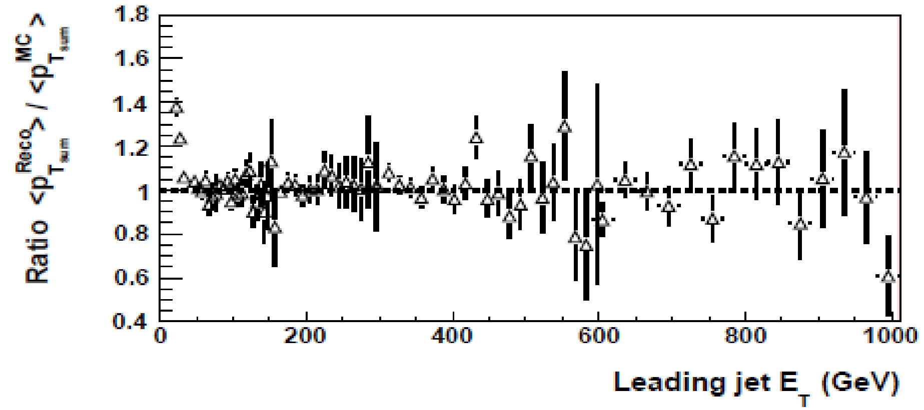
Underlying event measurement

- event selection
  - → ≥1 jet Cone R=0.7
    - E_T>10 GeV, |η|<2.5
- define transverse region wrt leading jet
  - → study particle production
    - tracks with p_T>1 GeV
  - → charge particle multiplicity
  - → average particle p_T





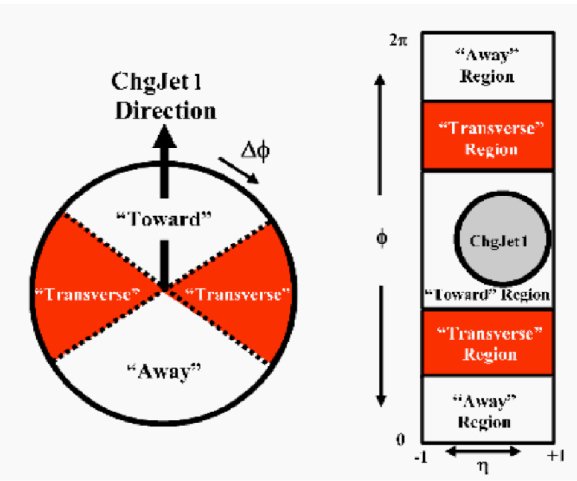
√s=14 TeV

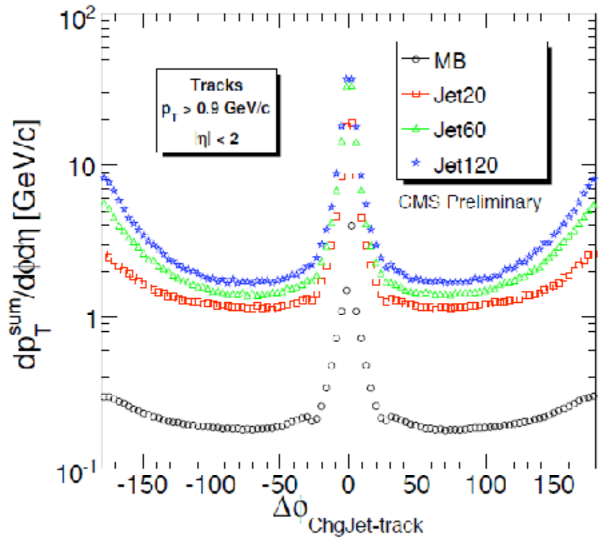


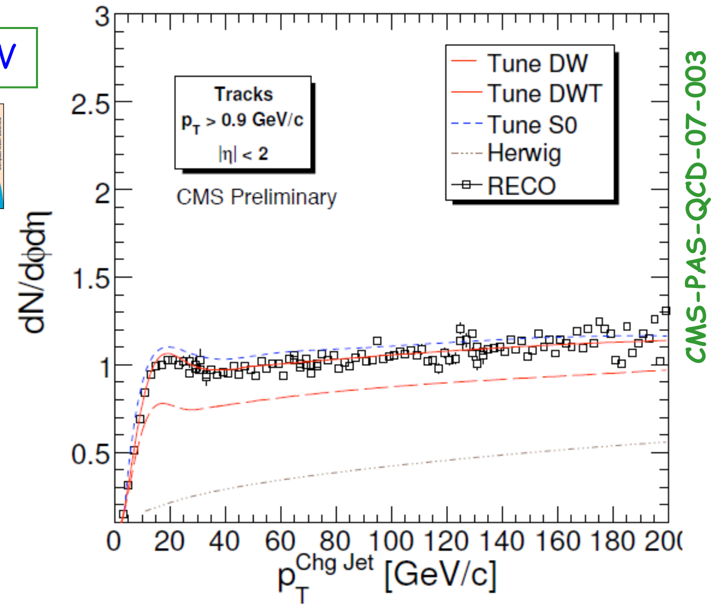
Underlying event structure

- selection (trigger on jets/MB)
  - → jets from charged particles
    - iterative cone R=0.5 ($|\eta|<2$)

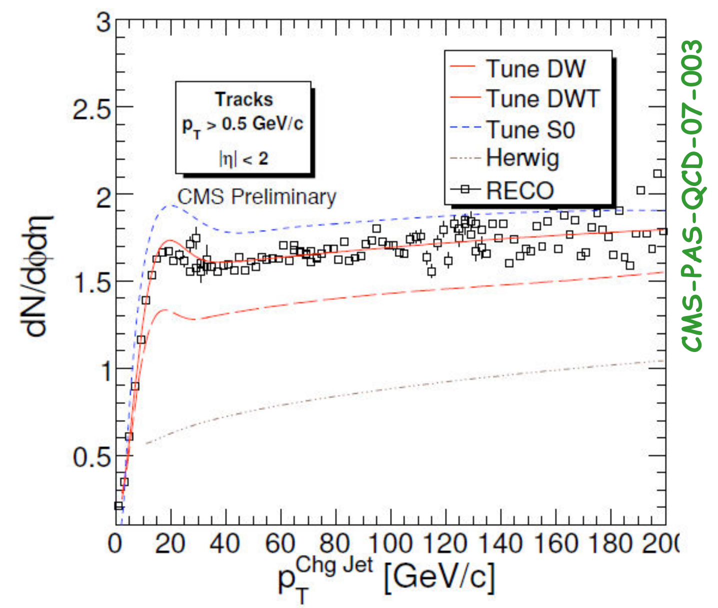
√s=14TeV







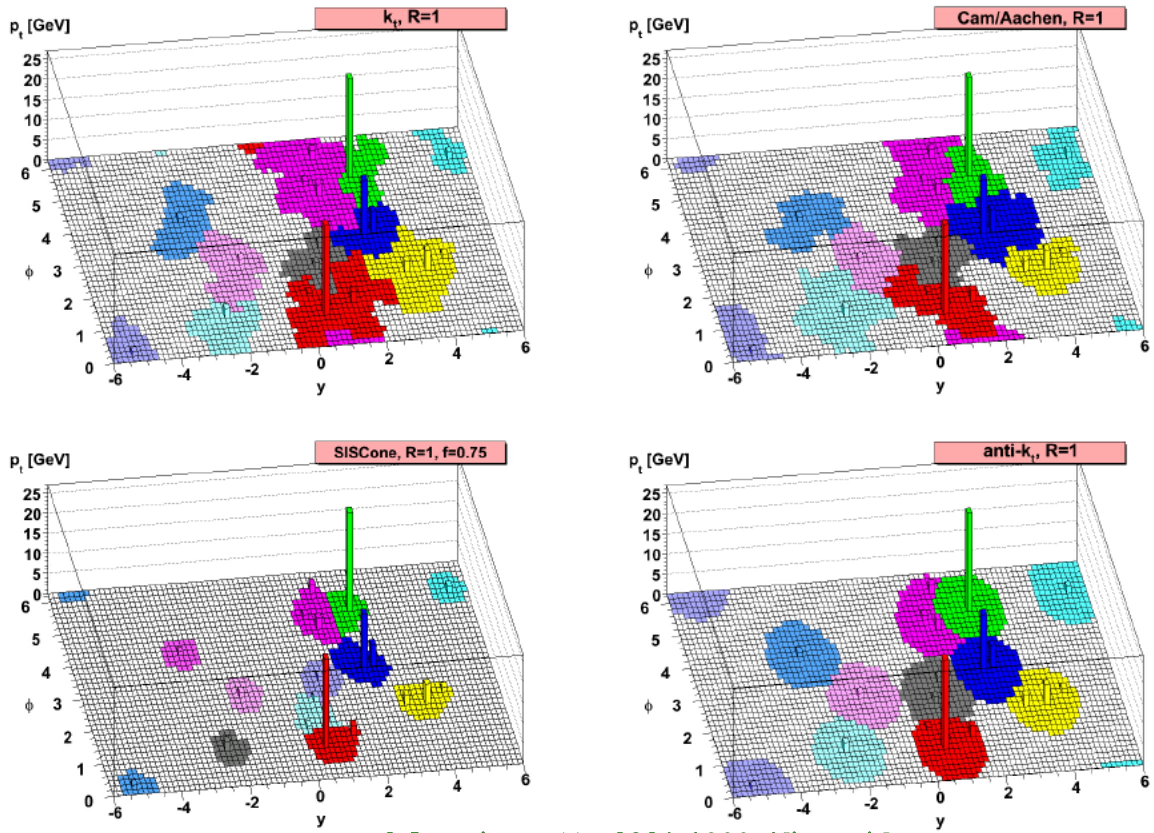
- measurement in transverse region
  - → charged particle multiplicity
    - distributions shown for 100 pb^{-1}
- importance of minimum track p_T
  - → more sensitivity to different models



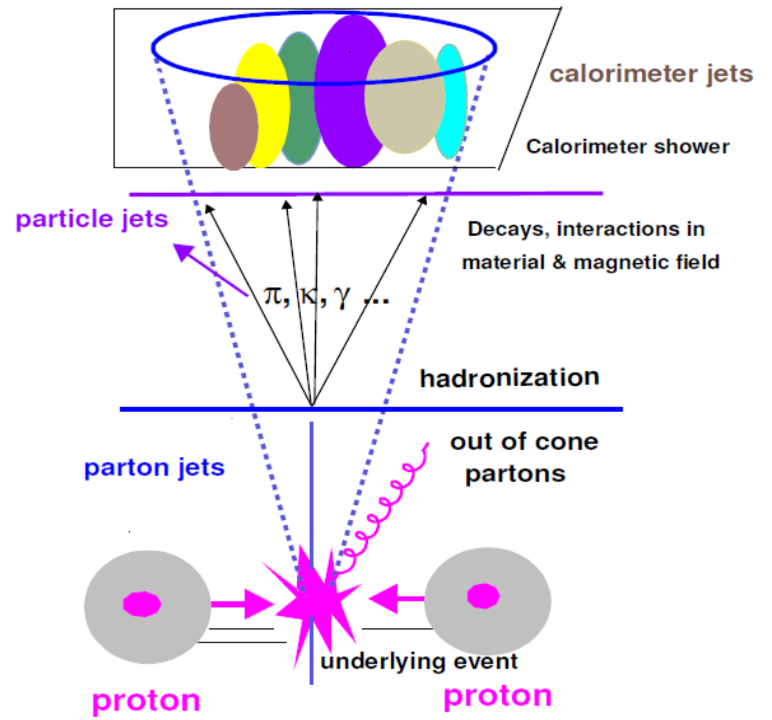
Jets

Jet physics

- need to define what a jet is
  - → jet algorithm
    - requirements: infra-red and collinear safe, …



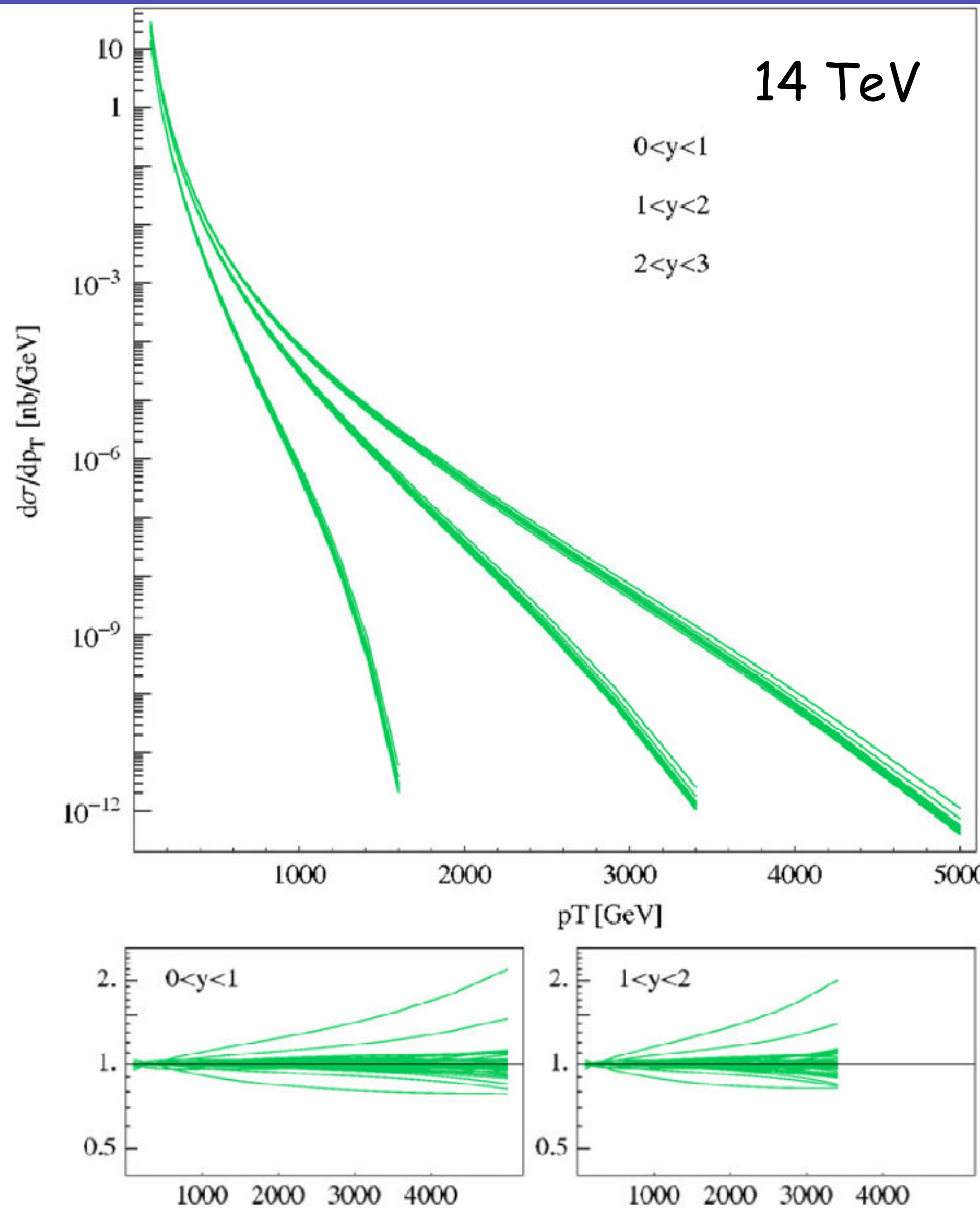
G.P. Salam arXiv:0906:1833v1[hep-ph]



- need to determine true jet energy
  - → jet energy calibration and unfolding of energy smearing
    - jet energy scale
    - jet energy resolution

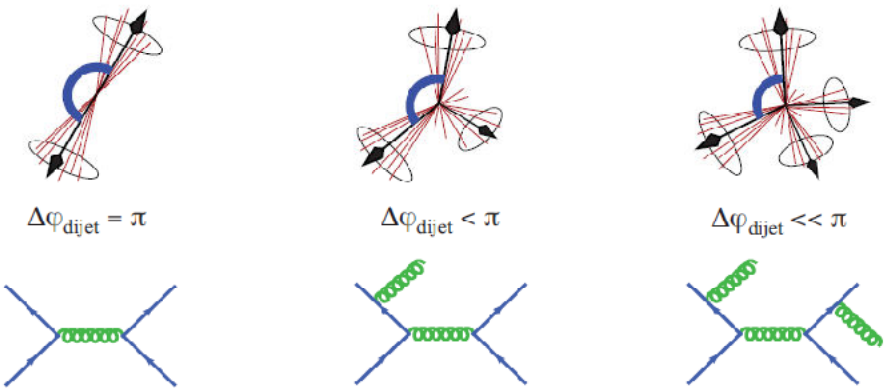
Jet production: observables

- inclusive jet production
- di-jet production
  - → azimuthal angular distribution
  - → di-jet invariant mass
  - → triple differential cross-section
  - → exclusive production, gap between jets, …
- multi-jet production
- jet shape determination



J.M.Campbell, J.W.Huston, W.J. Stirling Rep.Prog.Phys. 70 (2007) 89-193

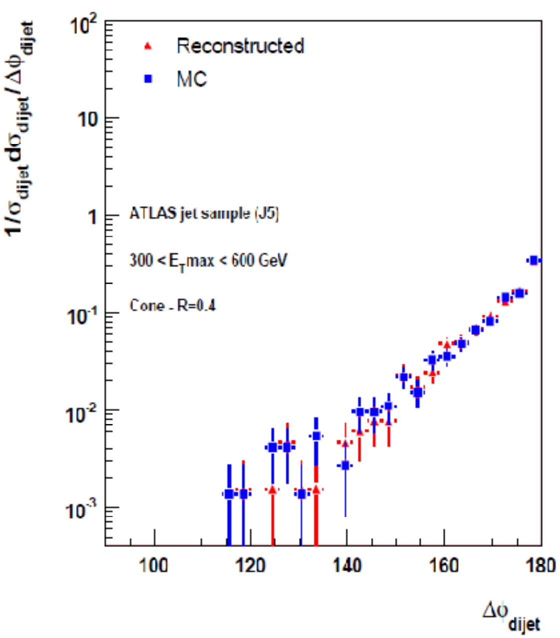
Di-jet azimuthal decorrelation

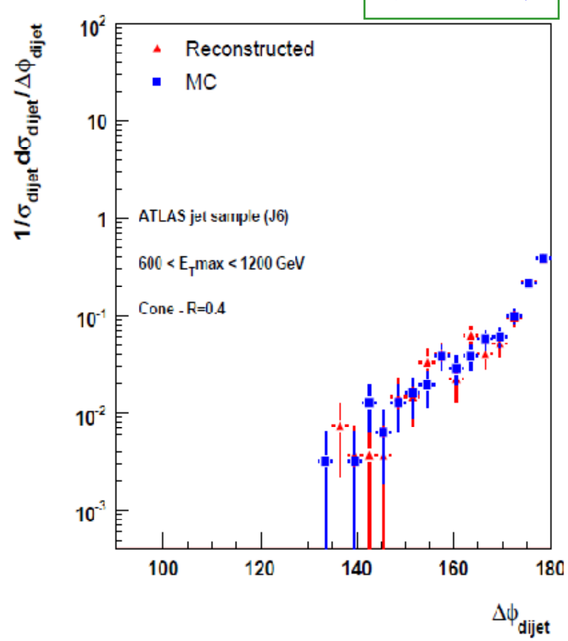


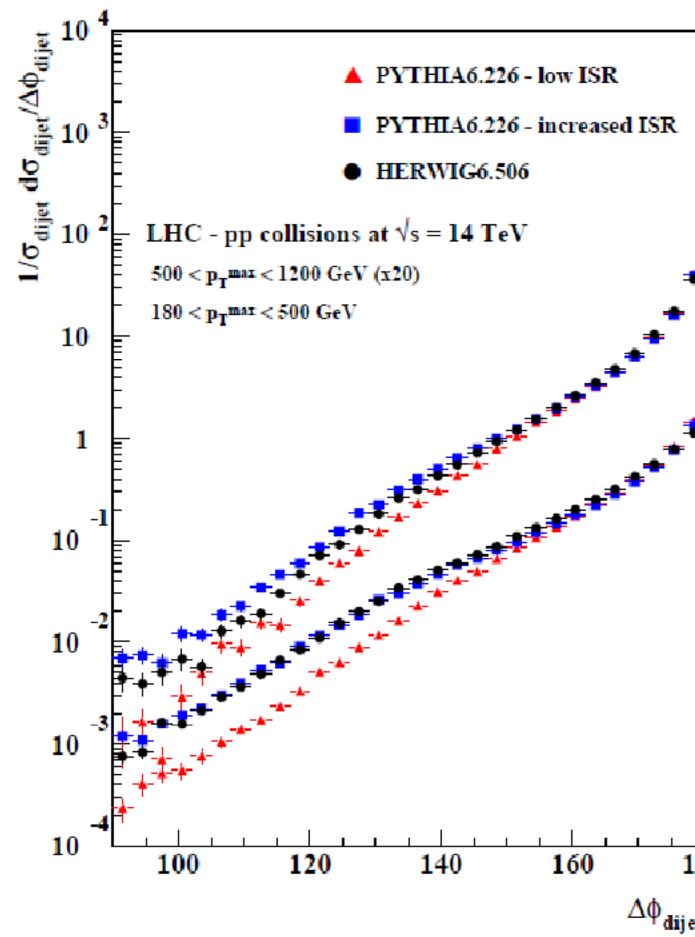
- event selection
  - → 2 jets (Cone R=0.7, |h|<0.5)
    - $E_{T,jet2}$ > 80 GeV

- sensitivity to modeling of radiation
  - → higher orders, parton showering

√s=14 TeV







ATLAS-PHYS-PUB-2006-013

Jet shape measurements

- global transverse thrust
  - → ½ for homogenous event

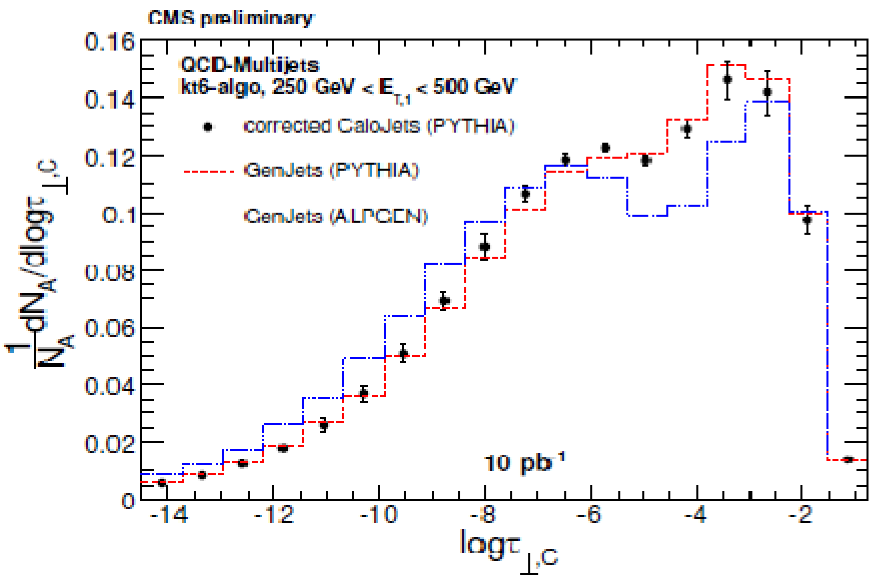
$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

global thrust minor

deviation from thrust axis

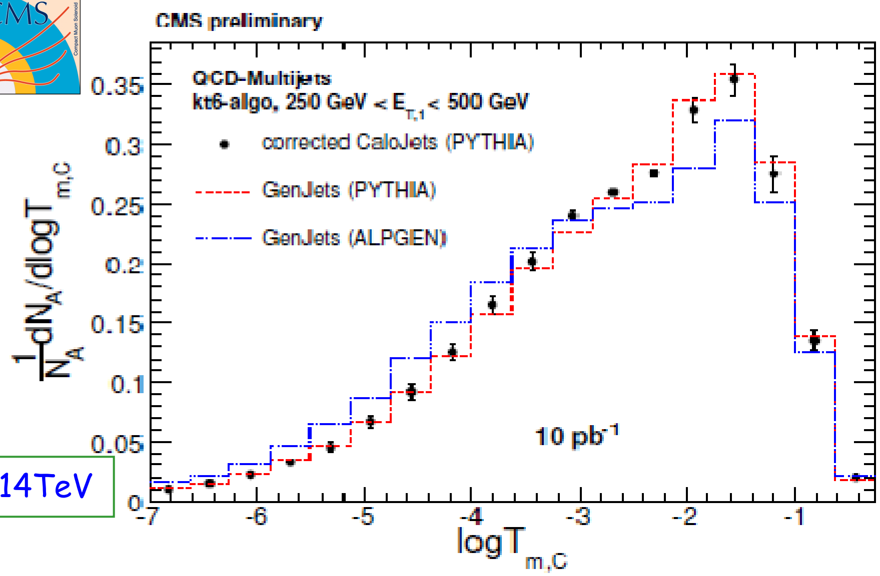
$$T_{m,g} \equiv \frac{\sum_i |p_{x,i}|}{\sum_i p_{\perp,i}} = \frac{\sum_i |(\vec{p} \times \vec{n}_B) \times \vec{n}_T|}{\sum_i p_{\perp,i}}.$$

- systematic uncertainties
  - → jet energy scale, jet energy resolution, reconstruction efficiency



CMS-PAS-QCD-08-003

√s=14TeV

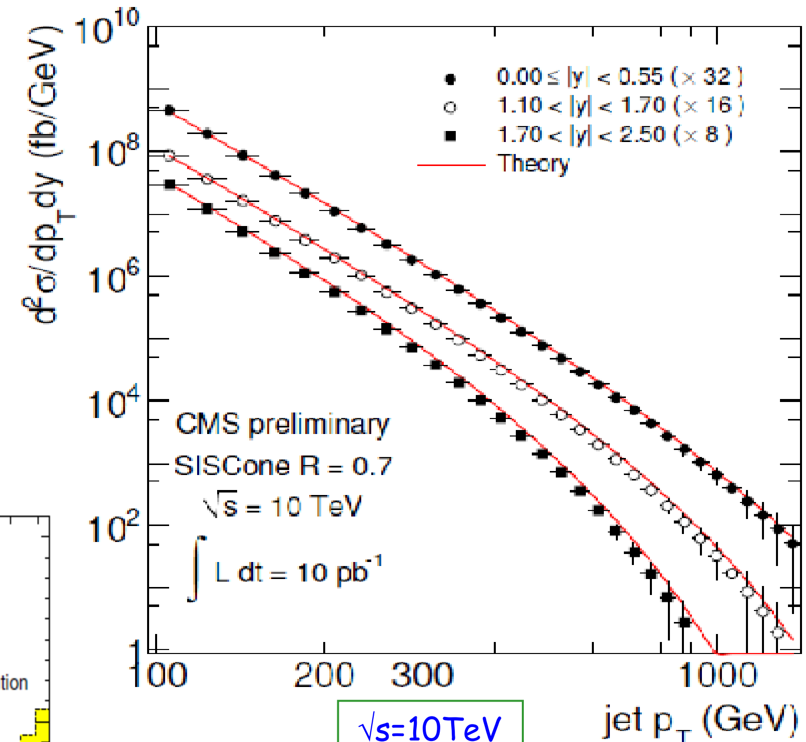


- sensitivity to modeling of multi-jet events
  - → insensitive to jet algorithm (mid point Cone, SISCone, kt studied)
  - → input for MC tuning

Inclusive jet cross-section

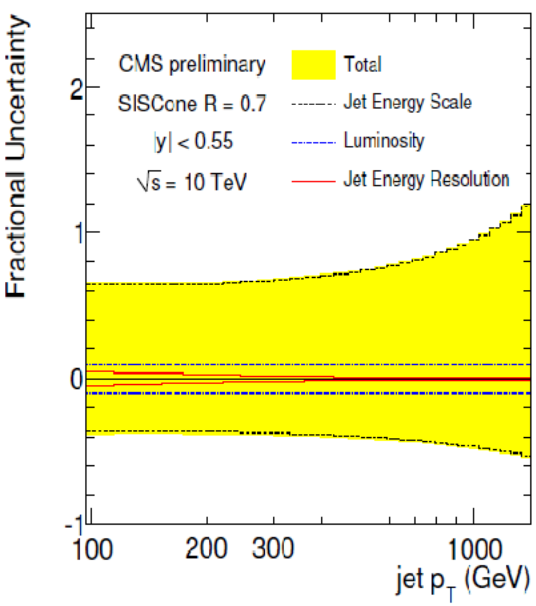
- event selection
  - → clean up (MET/ΣET < 0.3), jet trigger
- jet algorithm: SISCone
  - → R=0.7, overlap threshold of 0.75
- jet energy scale determination
  - → relative: η intercalibration with dijets
  - → absolute: γ/Z-jet balance
    - in-situ possible up to 600 GeV (10 pb^{-1})
- energy unsmearing via Ansatz function

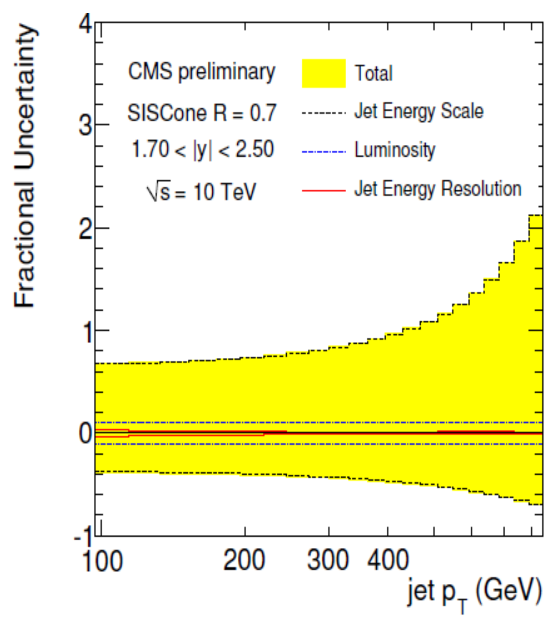
$$\frac{d^2\sigma}{dp_T dy} = \frac{C_{res}}{\mathcal{L}\cdot\varepsilon}\cdot\frac{N_{jets}}{\Delta p_T\cdot\Delta y}$$



√s=10TeV

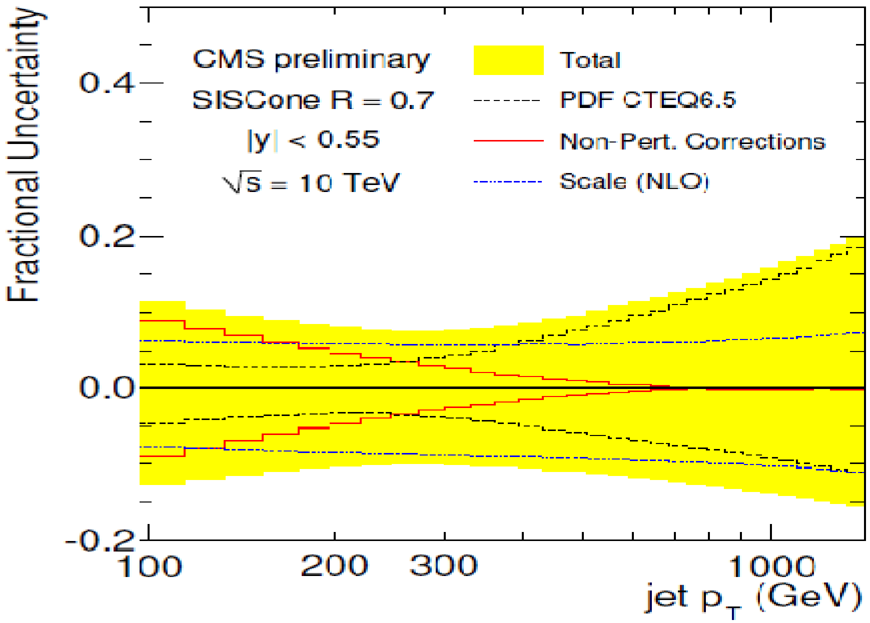
CMS-PAS-QCD-08-001

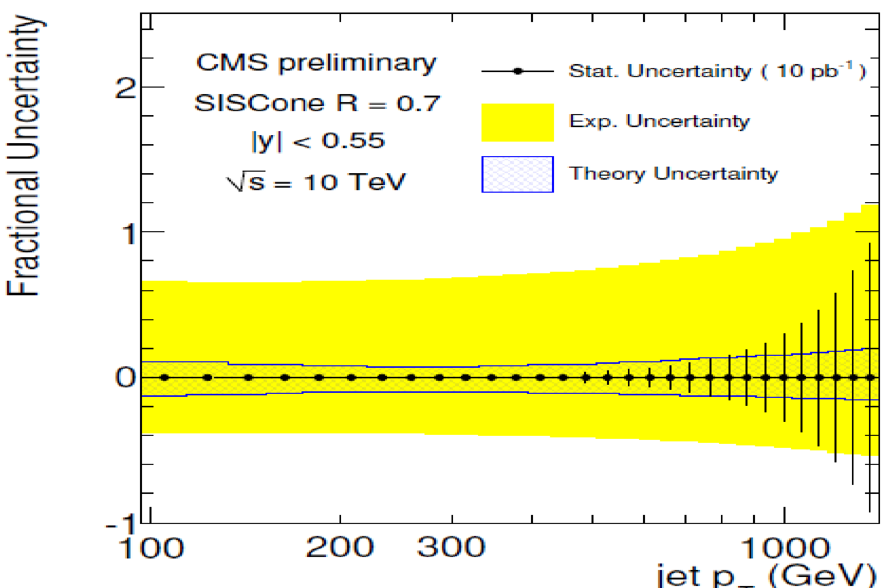




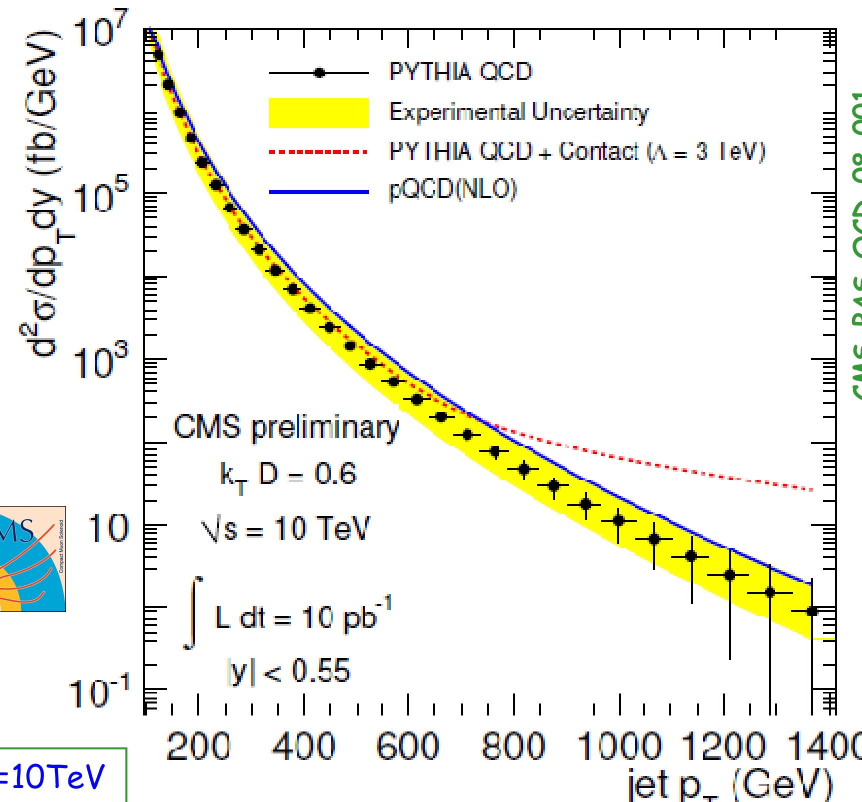
- systematic uncertainties
  - → jet energy scale: 10%
    - flat in E_T
  - → jet energy resolution: 10%
  - → luminosity: 10%

Inclusive jet cross-section



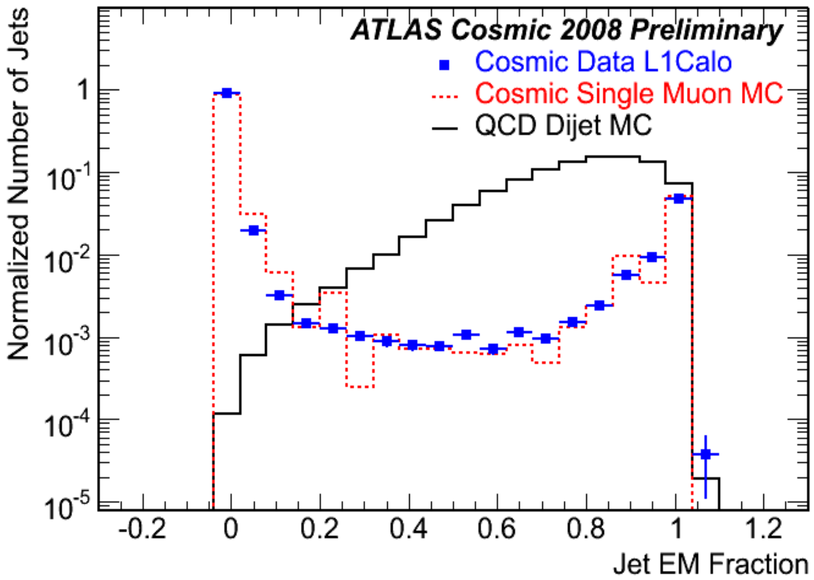


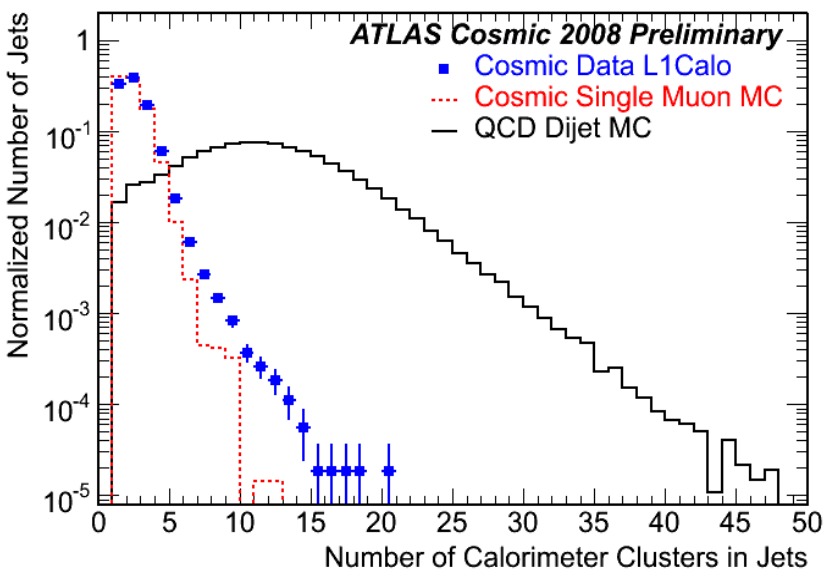
- theory prediction with NLOJET++
  - → hadronization correction via PYTHIA



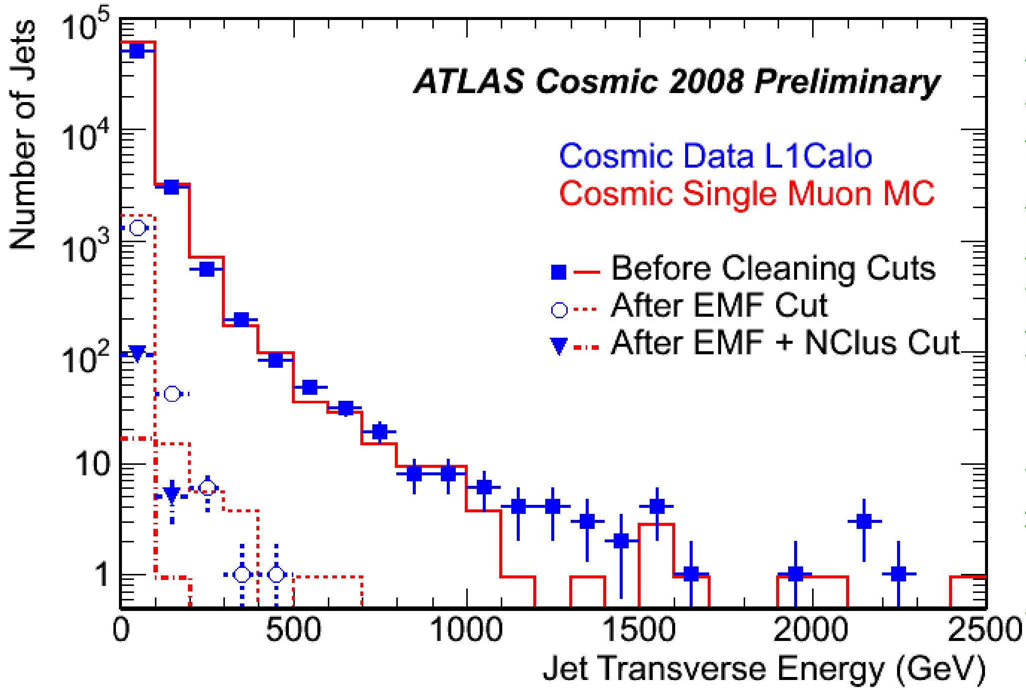
$\sqrt{s}$=10TeV

Jets from cosmic muon events





- cleaning cuts
  - → electromagnetic fraction of jet energy
  - → number of calorimeter clusters in jet



https://twiki.cern.ch/twiki/bin/view/Atlas/ApprovedCosmicPlotsJetEtMiss

Outlook

- first LHC physics run in 2010
  - → entering a new kinematic regime ($\sqrt{s}$ = 7 TeV up to 8-10 TeV)
- broad spectrum of QCD related measurements
  - → from soft processes (e.g. minimum bias) to hard processes (e.g. jet production) and in between (e.g. underlying event)
- important early measurements (due to large cross-section)
  - → need to establish precisely properties of 'standard' proton-proton interactions in this new kinematic regime
    - further insight in phenomenology of strong interaction
    - solid foundation for search of new physics processes

References

- ATLAS: Expected Performance of the ATLAS Experiment
  - CERN-OPEN-2008-020 or arXiv 0901.0512
- ATLAS: further public results
  - https://atlas-physco.web.cern.ch/atlas-physco/ATLASPubNotes.html
  - https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
- CMS: "Physics TDR"
  - CERN-LHCC-2006-001 or J.Phys. G 34 (2007) 995-1579
- CMS: "Post Physics TDR" Results
  - https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

- most (simulation) studies done for $\sqrt{s}$ = 14 TeV

  → recently studies 'published' for $\sqrt{s}$ = 10 TeV as well

Backup

LHC luminosity 900 GeV (scenario)

450 GeV collisions

Energy	Safe	Very Safe
450	1 e12	1 e11
1 TeV	2.5 e11	2.5 e10
3.5 TeV	3 e10	probe

- Time limited: 5 shifts
- No squeeze
- Low intensity – machine protection commissioning unlikely to be very advanced.
- ~2 weeks after first beam

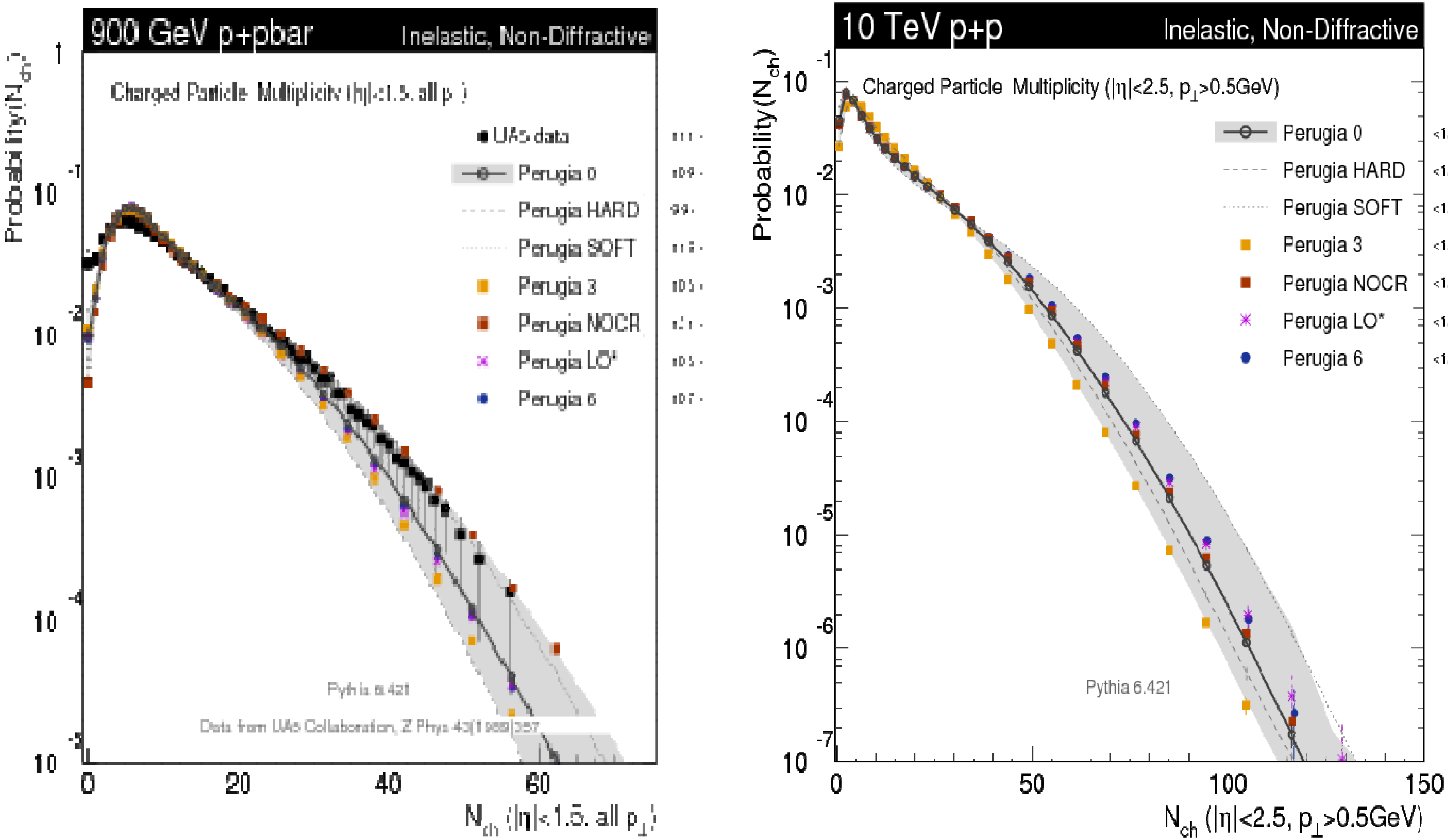
Number of bunches per beam	2	4	4
Collision schedule	2-1-2-1	4-3-4-1 (?)	4-3-4-1 (?)
Particles per bunch	3×10^{10}	4×10^{10}	6×10^{10}
Beam intensity*	6×10^{10}	1.6×10^{11}	2.4×10^{11}
beta* [m]	10	10	10
Luminosity [$cm^{-2}s^{-1}$]	1.1×10^{27}	5.9×10^{27}	1.3×10^{28}

M. Lamont, LPC meeting, Sep 14, 2009

LHC luminosity evolution (scenario)

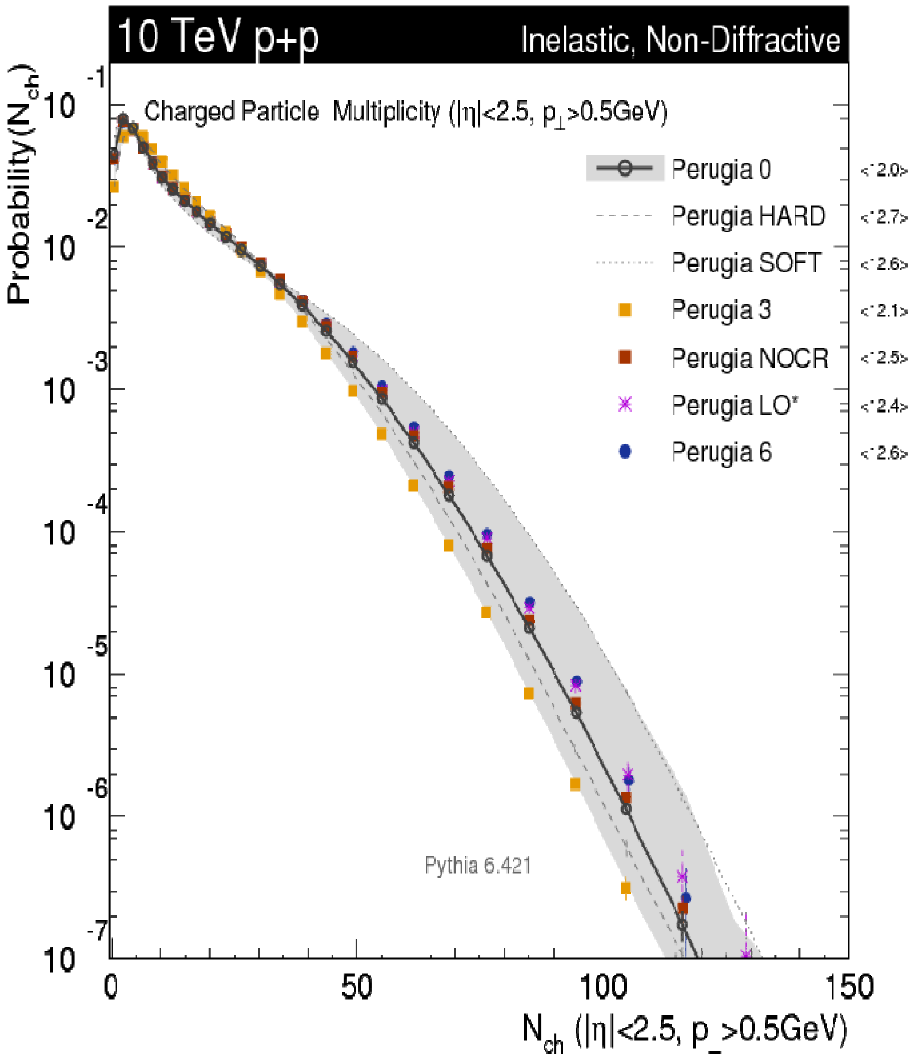
Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrate d	% nominal
1	Beam commissioning						
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}	
3		43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}	
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8
6	Shift to higher energy: approx 4 weeks	Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity					
7	4 – 5 TeV (5 TeV luminosity numbers quoted)	156	7×10^{10}	2	4.9×10^{31}	~26 pb^{-1}	3.4
8	50 ns – nominal Xing angle	144	7×10^{10}	2	4.4×10^{31}	~23 pb^{-1}	3.1
9	50 ns	288	7×10^{10}	2	8.8×10^{31}	~46 pb^{-1}	6.2
10	50 ns	432	7×10^{10}	2	1.3×10^{32}	~69 pb^{-1}	9.4
11	50 ns	432	9×10^{10}	2	2.1×10^{32}	~110 pb^{-1}	12

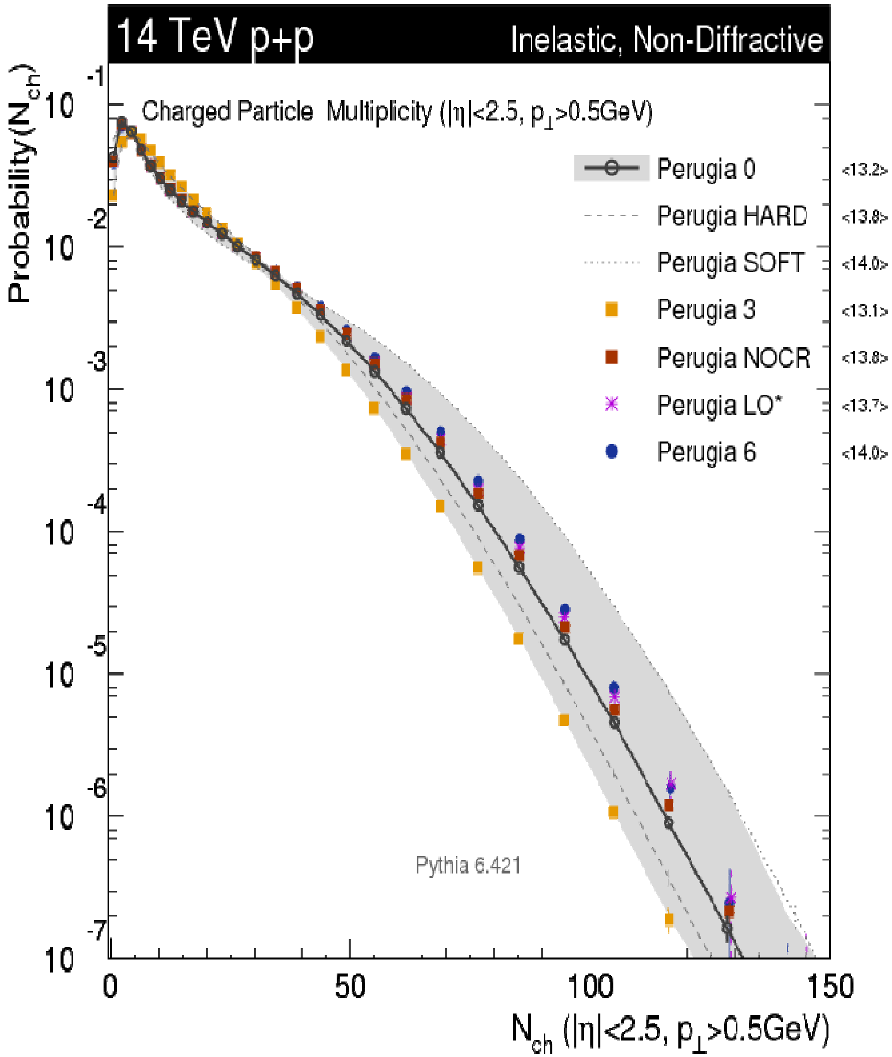
900 GeV (pbarp) vs. 10 TeV (pp)



P. Skands, http://home.fnal.gov/~skands/leshouches-plots/

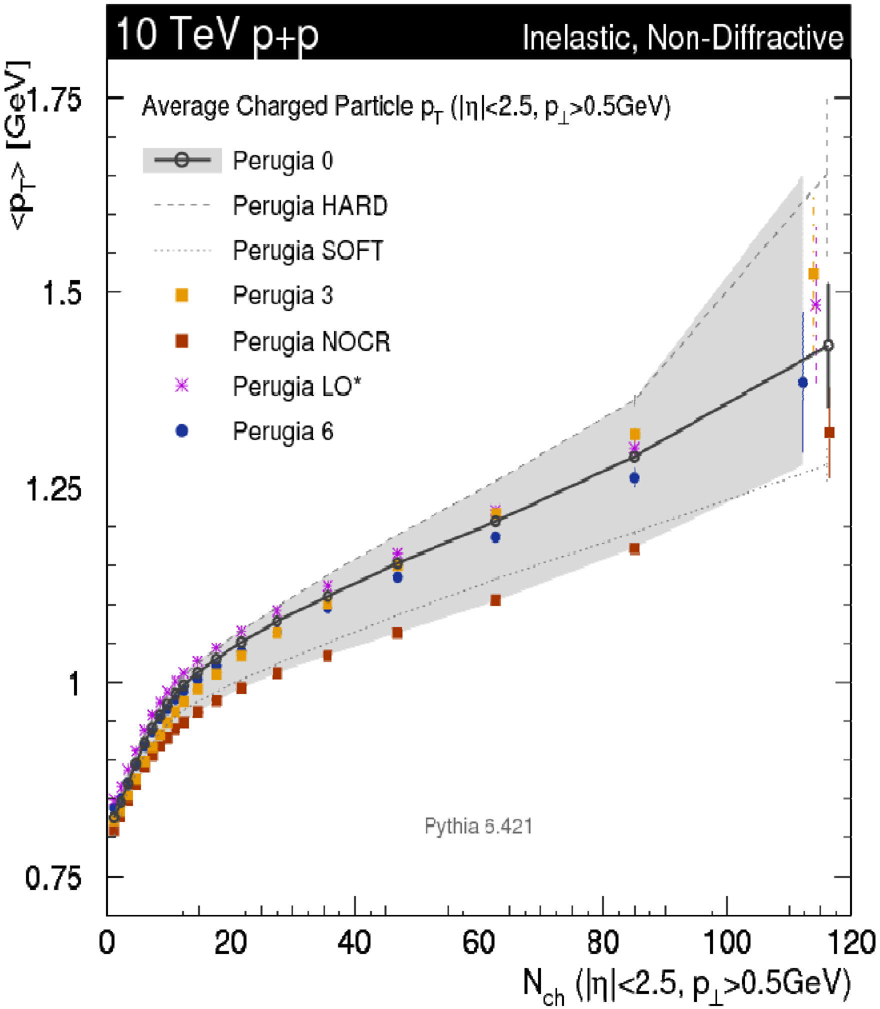
Perugia tuning: LHC prediction

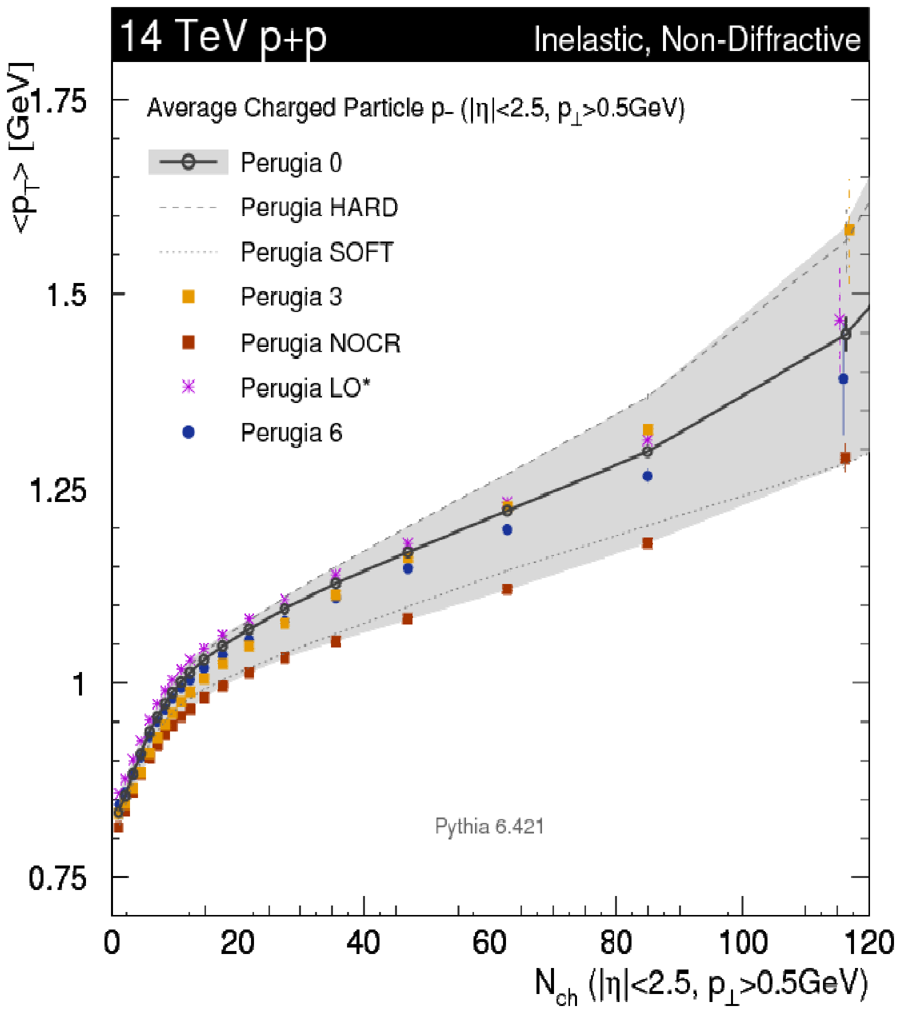




P. Skands, http://home.fnal.gov/~skands/leshouches-plots/

Perugia tuning: LHC prediction





P. Skands, http://home.fnal.gov/~skands/leshouches-plots/

Minimum bias predictions : 'Perugia' tunes

Parameter	Type	S0A-Pro	P-0	P-HARD	P-SOFT	P-3	P-NOCR	P-X	P-6
MSTP(51)	PDF	7	7	7	7	7	7	20650	10042
MSTP(52)	PDF	1	1	1	1	1	1	2	2
MSTP(64)	ISR	2	3	3	2	3	3	3	3
PARP(64)	ISR	1.0	1.0	0.25	2.0	1.0	1.0	2.0	1.0
MSTP(67)	ISR	2	2	2	2	2	2	2	2
PARP(67)	ISR	4.0	1.0	4.0	0.5	1.0	1.0	1.0	1.0
MSTP(70)	ISR	2	2	0	1	0	2	2	2
PARP(62)	ISR	-	-	1.25	-	1.25	-	-	-
PARP(81)	ISR	-	-	-	1.5	-	-	-	-
MSTP(72)	ISR	0	1	1	0	2	1	1	1
PARP(71)	FSR	4.0	2.0	4.0	1.0	2.0	2.0	2.0	2.0
PARJ(81)	FSR	0.257	0.257	0.3	0.2	0.257	0.257	0.257	0.257
PARJ(82)	FSR	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
MSTP(81)	UE	21	21	21	21	21	21	21	21
PARP(82)	UE	1.85	2.0	2.3	1.9	2.2	1.95	2.2	1.95
PARP(89)	UE	1800	1800	1800	1800	1800	1800	1800	1800
PARP(90)	UE	0.25	0.26	0.30	0.24	0.32	0.24	0.23	0.22
MSTP(82)	UE	5	5	5	5	5	5	5	5
PARP(83)	UE	1.6	1.7	1.7	1.5	1.7	1.8	1.7	1.7
MSTP(88)	BR	0	0	0	0	0	0	0	0
PARP(79)	BR	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
PARP(80)	BR	0.01	0.05	0.01	0.05	0.03	0.01	0.05	0.05
MSTP(91)	BR	1	1	1	1	1	1	1	1
PARP(91)	BR	2.0	2.0	1.0	2.0	1.5	2.0	2.0	2.0
PARP(93)	BR	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
MSTP(95)	CR	6	6	6	6	6	6	6	6
PARP(78)	CR	0.2	0.33	0.37	0.15	0.35	0.0	0.33	0.33
PARP(77)	CR	0.0	0.9	0.4	0.5	0.6	0.0	0.9	0.9
MSTJ(11)	HAD	5	5	5	5	5	5	5	5
PARJ(21)	HAD	0.313	0.313	0.34	0.28	0.313	0.313	0.313	0.313
PARJ(41)	HAD	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
PARJ(42)	HAD	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
PARJ(46)	HAD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PARJ(47)	HAD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

P. Skands, arXiv:0905.3418v1 [hep-ph]

MB: cross-section, efficiency, acceptance

- example cross-section composition for two MC models

√s=14 TeV

Process	Cross-section (mb)	
	PHOJET	PYTHIA
non-diff.	69	55
single diff.	11	14
double diff.	4	10
central diff.	1	-
total inelastic	85	79
elastic	35	23
total	120	102

CERN-OPEN-2008-020

- efficiency of MB triggers
- acceptance of MB triggers
  - → efficiency weighted by the fraction of the inelastic cross-section

efficiency	MBTS_1_1	MBTS_2	SP	SP & EF Tracks
Non-diffractive	99%	100%	100%	100%
Double-diffractive	54%	83%	66%	65%
Single-diffractive	45%	69%	57%	57%
Beam-gas	40%	54%	47%	40%

acceptance	MBTS_1_1	MBTS_2	SP	SP & EF Tracks
Non-diffractive	69%	70%	70%	70%
Double-diffractive	7%	10%	8%	8%
Single-diffractive	8%	12%	10%	10%

Minimum bias: track reconstruction

- track selection cuts for MB analysis
  - → $p_T > 150$ MeV
  - → $|\eta| < 2.5$

Quality cuts	No. of b-layer hits ≥ 1 No. of Silicon hits ≥ 5
Resolution cuts	$\lvert\sigma_{d_0}\rvert < 1.6$ mm $\lvert\sigma_{z_0}\rvert < 6.0$ mm $\lvert\sigma_{\phi}\rvert < 0.03$ $\lvert\sigma_{\theta}\rvert < 0.015$ $\lvert\sigma_{q/p_T}\rvert < 0.0003\ (\text{GeV})^{-1}$
Track-to-vertex cut	$N_\sigma < 3$

Cut	% Cut All	% Cut Primary tracks	% Cut Secondary tracks
b-layer hit	15.9	8.5	46.8
cov_{d0}	11.5	6.0	34.2
cov_{z0}	9.4	5.0	27.4
cov_{ϕ}	8.9	5.1	24.3
cov_{θ}	4.9	4.2	8.2
cov_{q/p_T}	6.4	4.3	14.9
Quality	15.9	8.5	46.8
Resolution	16.7	10.9	40.4
Q || R	24.6	15.6	62.1
Track-to-Vtx	30.7	16.9	87.8
η || p_T	1.2	1.3	0.9
Total	38.6	24.6	96.5

ATLAS

$\sqrt{s}$=14 TeV

CERN-OPEN-2008-020