MULTIPLE PARTON INTERACTIONS IN SOFT QCD MEASUREMENTS

(LHC EXPERIMENTS OVERVIEW)

ALDEN STRADLING

(ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS)

8 SEPTEMBER 2014

INTRO AND HEADLINERS

- Multi-parton interactions (MPI) in p-p collisions are tricky to measure and rapidly buried in other signal
  - Central to underling event (UE) modeling
  - Rapid increase in MPI with rising $\sqrt{s}$ (LHC, Tevatron, etc)
    - Small-x partons become visible to higher-energy probes as their color charges can now be resolved
    - Number of small-x partons increases dramatically
    - Primarily low-momentum t-channel exchanges
- Coexists with Initial State Radiation (ISR), Final State Radiation (FSR), beam remnants, beam backgrounds, and (of course) the hard interaction (if any). Pileup makes all of this far worse.
- Significant impact on all major studies at hadron colliders.

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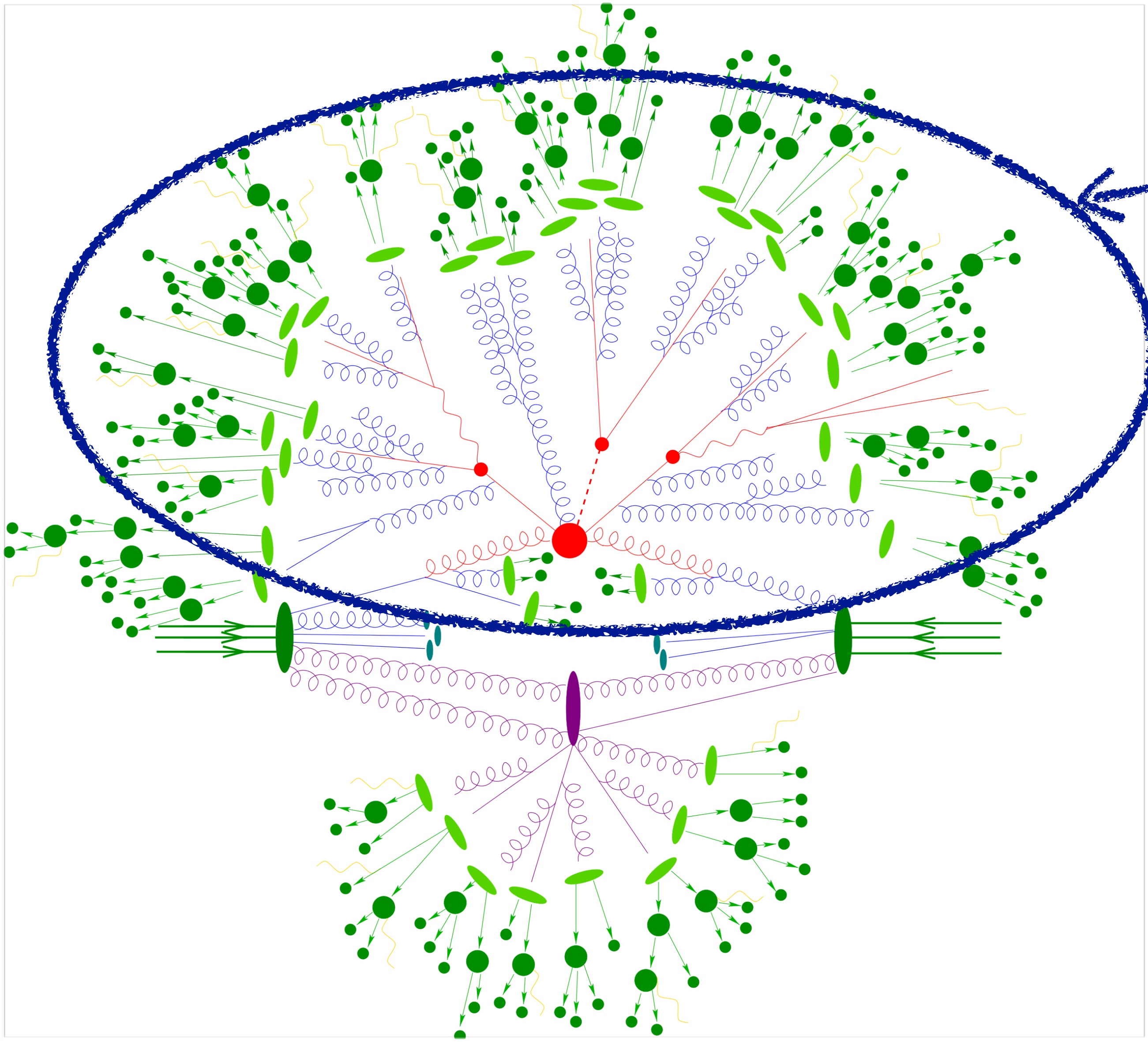
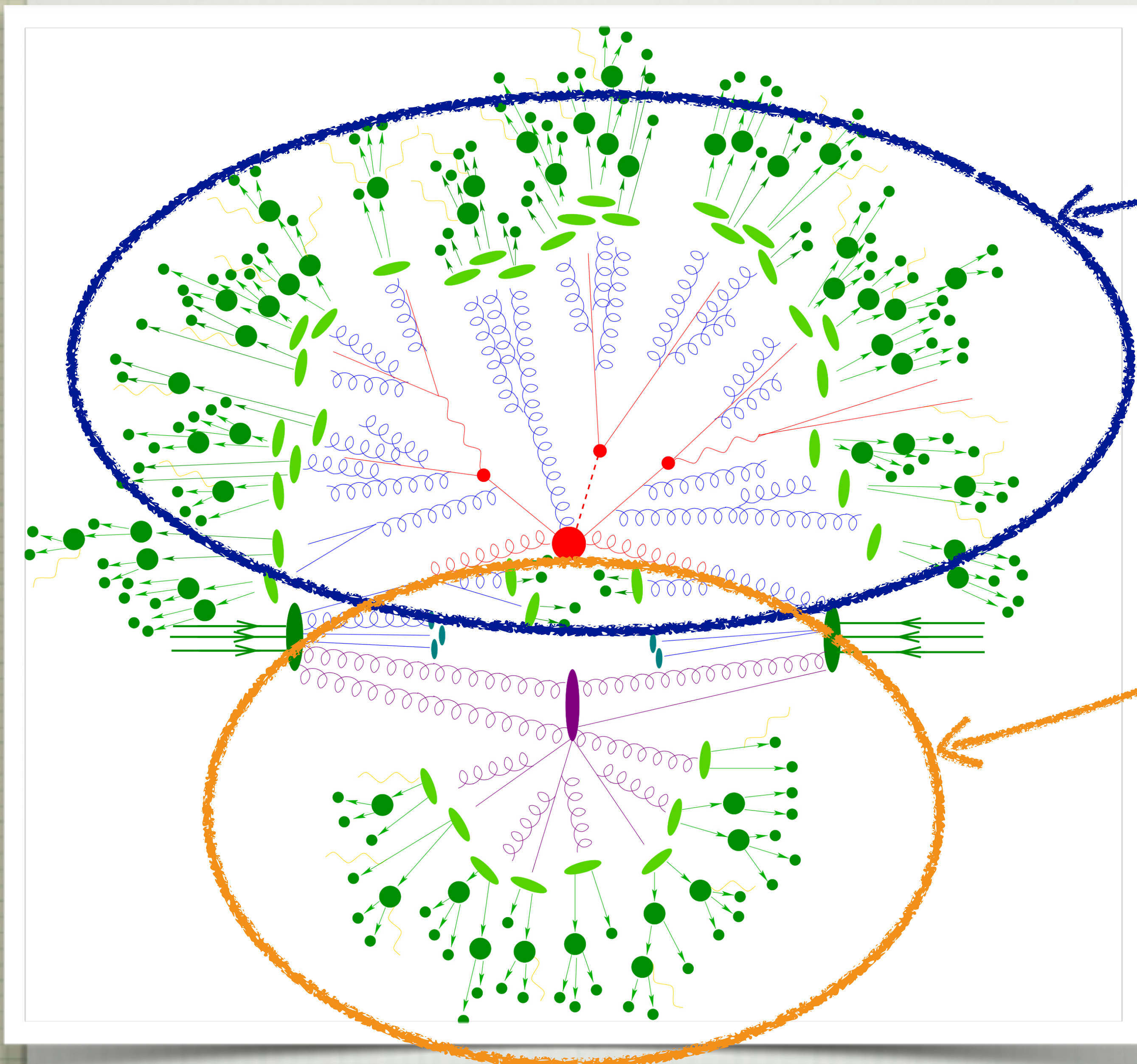


HARD INTERACTION (THE MAIN EVENT)



HARD INTERACTION (THE MAIN EVENT)

UNDERLYING EVENT (ISR, FSR, REMNANTS)

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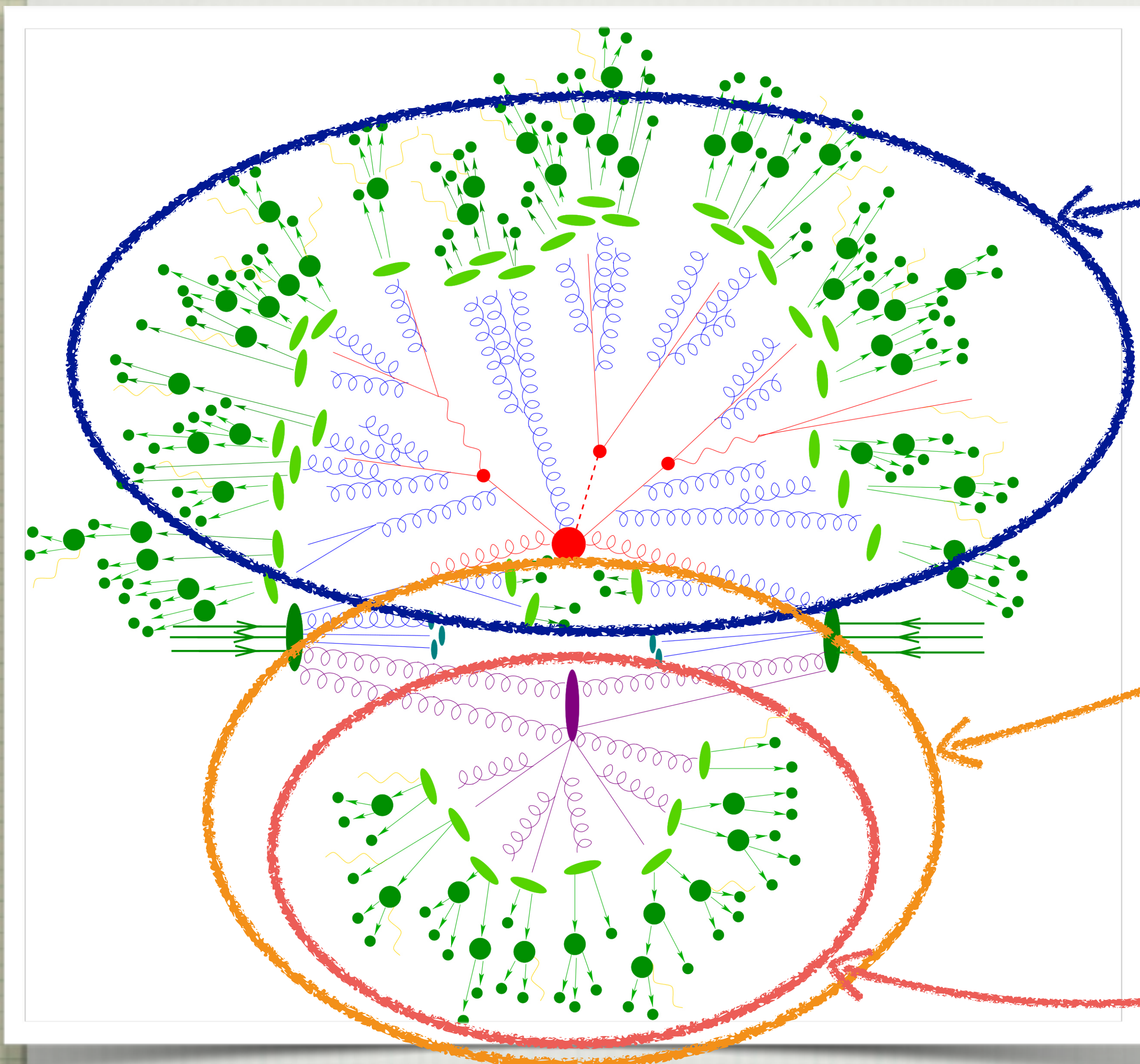


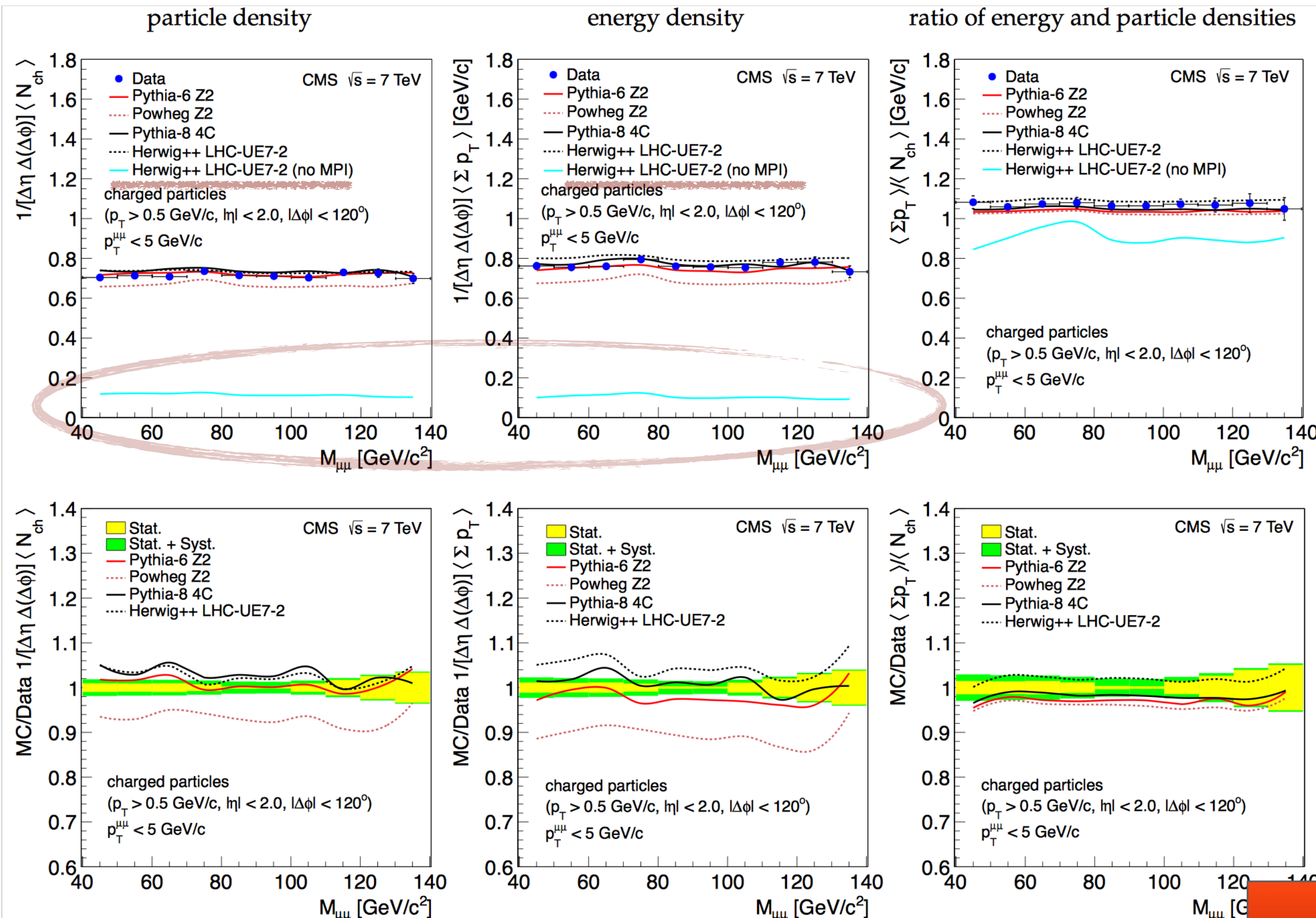
HARD INTERACTION (THE MAIN EVENT)

UNDERLYING EVENT (ISR, FSR, REMNANTS)

MPI, ALMOST INDEPENDENT OF HARD SCATTER GEOMETRY

SIGNIFICANT EFFECT...

http://arxiv.org/pdf/1204.1411v2.pdf



CMS

BASIC GENERATORS

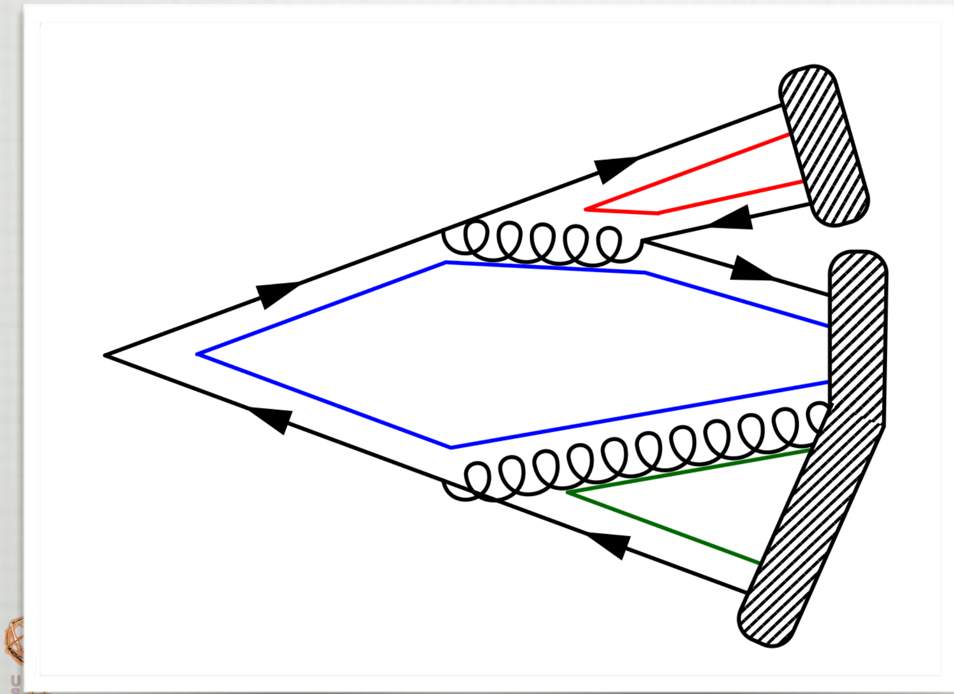
https://cds.cern.ch/record/1706286

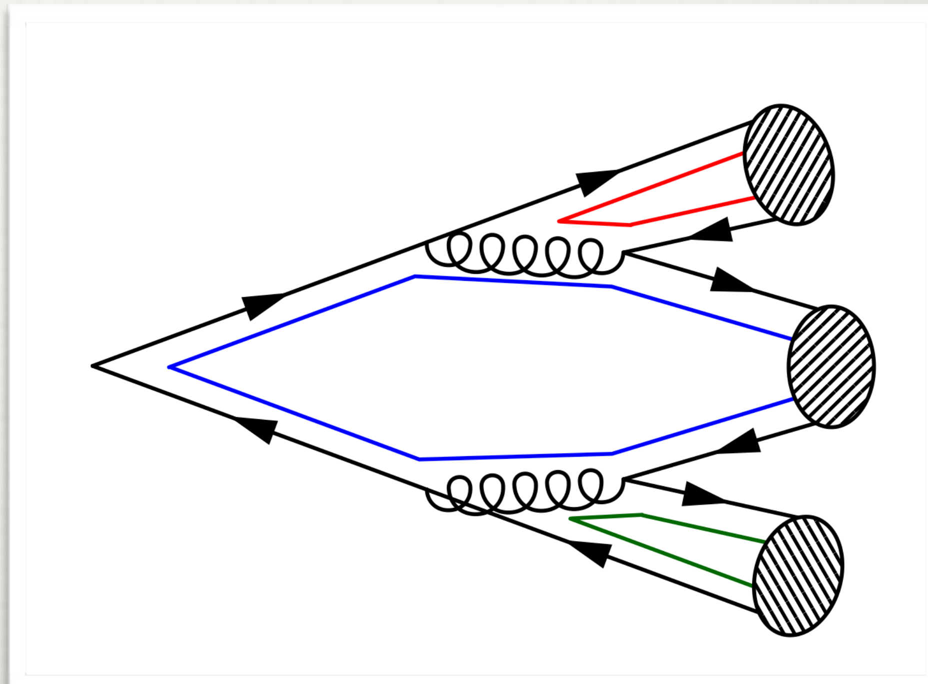
STRING MODEL (PYTHIA):

- LINEAR CONFINEMENT
- SPLIT STRINGS INTO HADRONS
- GOOD KINEMATICS
- POOR FINAL STATE FLAVOR DESCRIPTION

CLUSTER MODEL (HERWIG):

- PRE-CONFINEMENT
  - CLUSTERS INDEPENDENT OF HARD PROCESS SCALE
  - DEPENDENT ON QCD AND SHOWER SCALE
- DECAY CLUSTERS INTO HADRONS
- KINEMATICS NOT AS WELL MODELED
- BETTER FINAL STATE FLAVOR DESC.





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MC (IN)COMPATIBILITIES

- There's a vast variety of generators, PDFs and tunes to investigate
- To simplify — common comparison generators across the experiments are Pythia 6.4, Pythia 8.1 and Herwig++
  - Cosmic ray models are of interest to each experiment and for development, but are not used here as a comparison basis. There are some examples in the backup slides, including EPOS, QSGJET, DIPSY, and SIBYLL
- Common PDFs: for the most part, all experiments use the PDF set associated with a generator/tune combination
- The most useful common tunes:
  - Pythia 6.4: Perugia 0
  - Pythia 8.1: Default
  - Herwig++ (various)
- There are still incompatibilities in some results due to different generator definitions... take with a grain of salt when comparing experiments.

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MC PARAMETERS

http://indico.cern.ch/event/184925/session/4/contribution/19/material/slides/0.pdf

- There are a number of ways to modify the Pythia generators to tune the MPI model, since it has been added systematically
  - Primary tweaks include
    - Energy cutoff for MPI activity (prevents MPI from becoming infinite as p_T decreases
    - Energy rescaling power for the p_{T0} cutoff
    - Change ordering between virtuality, p_T and rapidity
    - Color reconnection range
    - Hadronic matter distribution

$$p_{T_0}(\sqrt{s}) = p_{T_{0_{ref}}} \times \left(\frac{\sqrt{s}}{E_{CM}^{ref}}\right)^{E_{rescale}^{pow}}$$

$$\rho(r,x) \propto \frac{1}{a^3(x)} exp\left(\frac{r^2}{a^2(x)}\right),$$

$$a(x) = a_0(1 + a_1 ln(1/x))$$

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MC TUNING

- The process is cyclical:
  1. Model the interactions we have seen at previous accelerators
  2. Measure soft QCD distributions
  3. Use as a standard candle
  4. Verify/expand our models and generator assumptions
  5. Use results to plan more precise measurements and searches
  6. Goto 2.
- Using manual tuning has gotten us this far
- Automated tuning using PROFESSOR
  - The ideal (goal) is to tune the model for one observable in one process and get a useful prediction for that observable in another final state
  - Automation can expedite exploration of the tuning space for each model
- CMS and ATLAS have some overlap via the CDPSTS2-4j (later)

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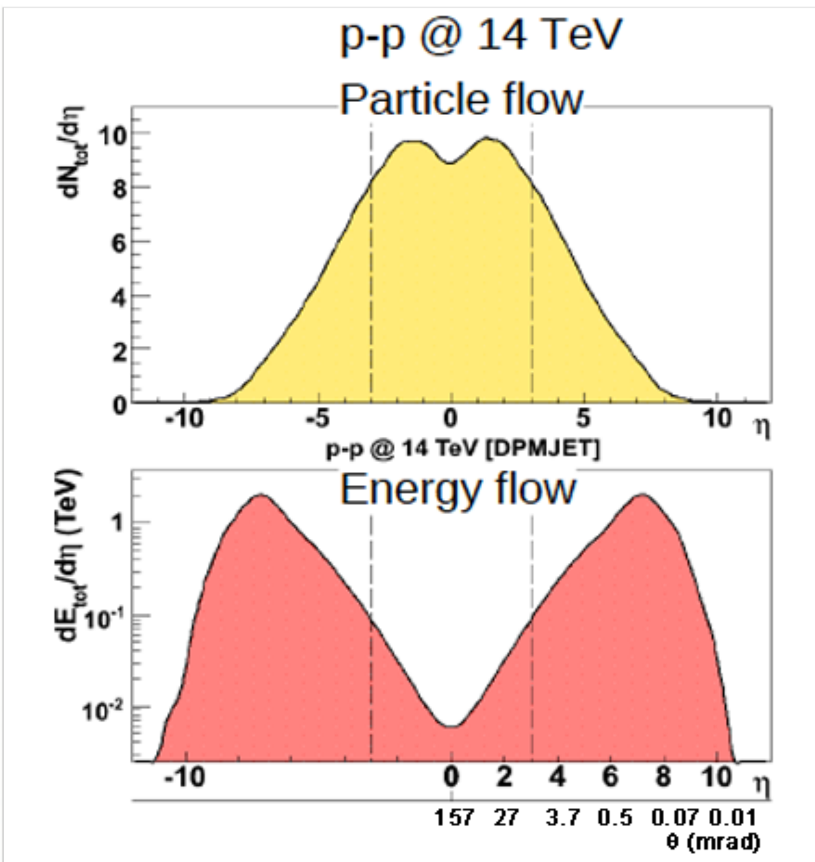
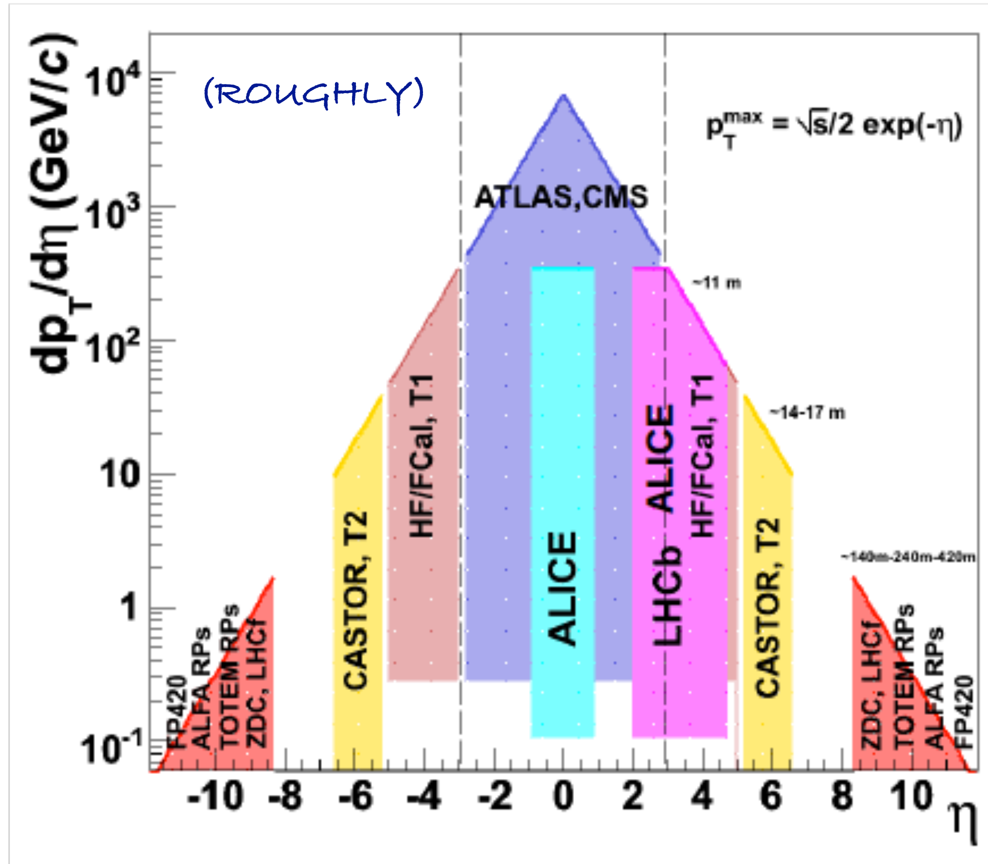
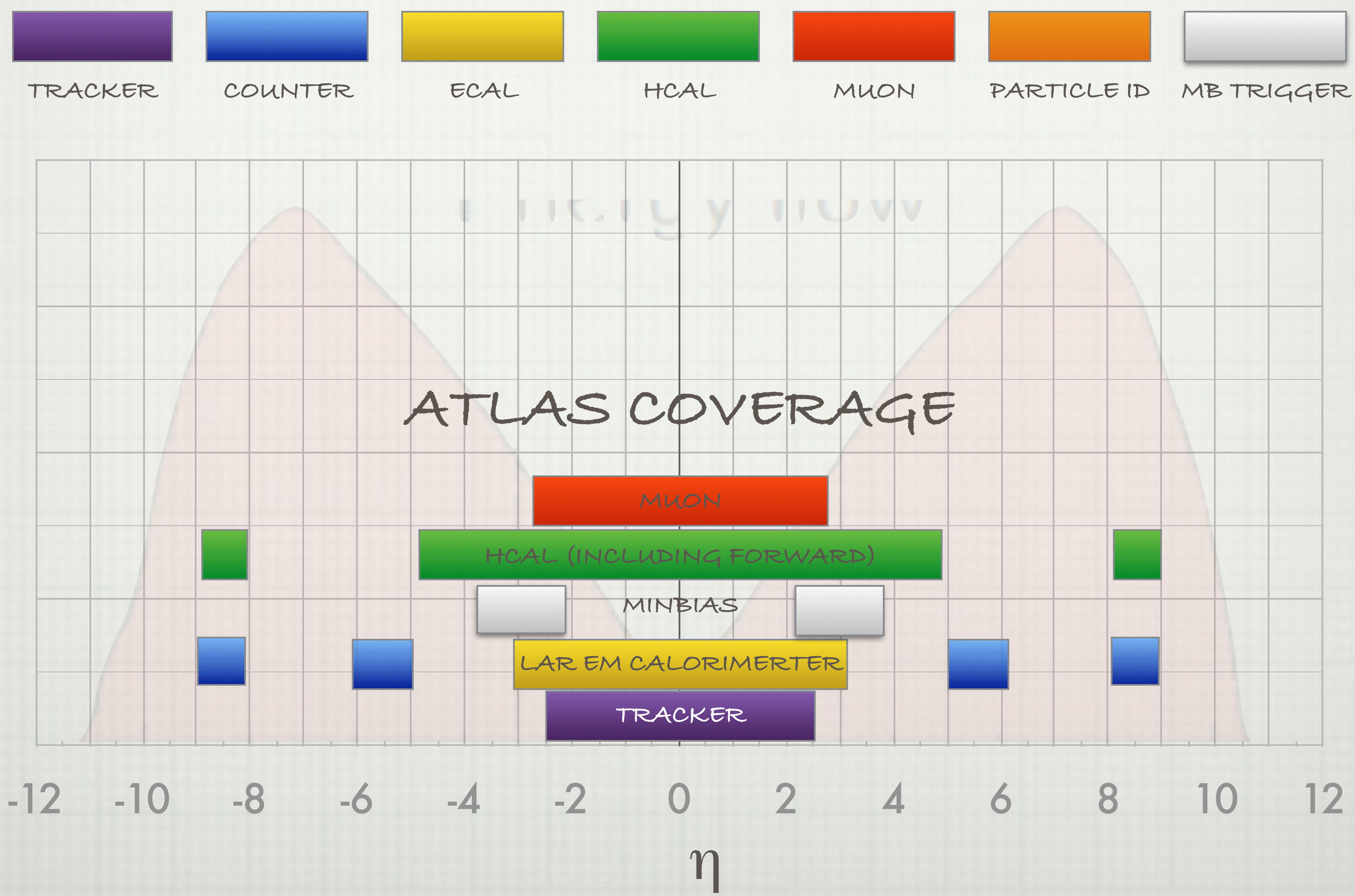
DETECTOR COVERAGE





DAVID D'ENTERRIA, 2008

DETECTOR COVERAGE



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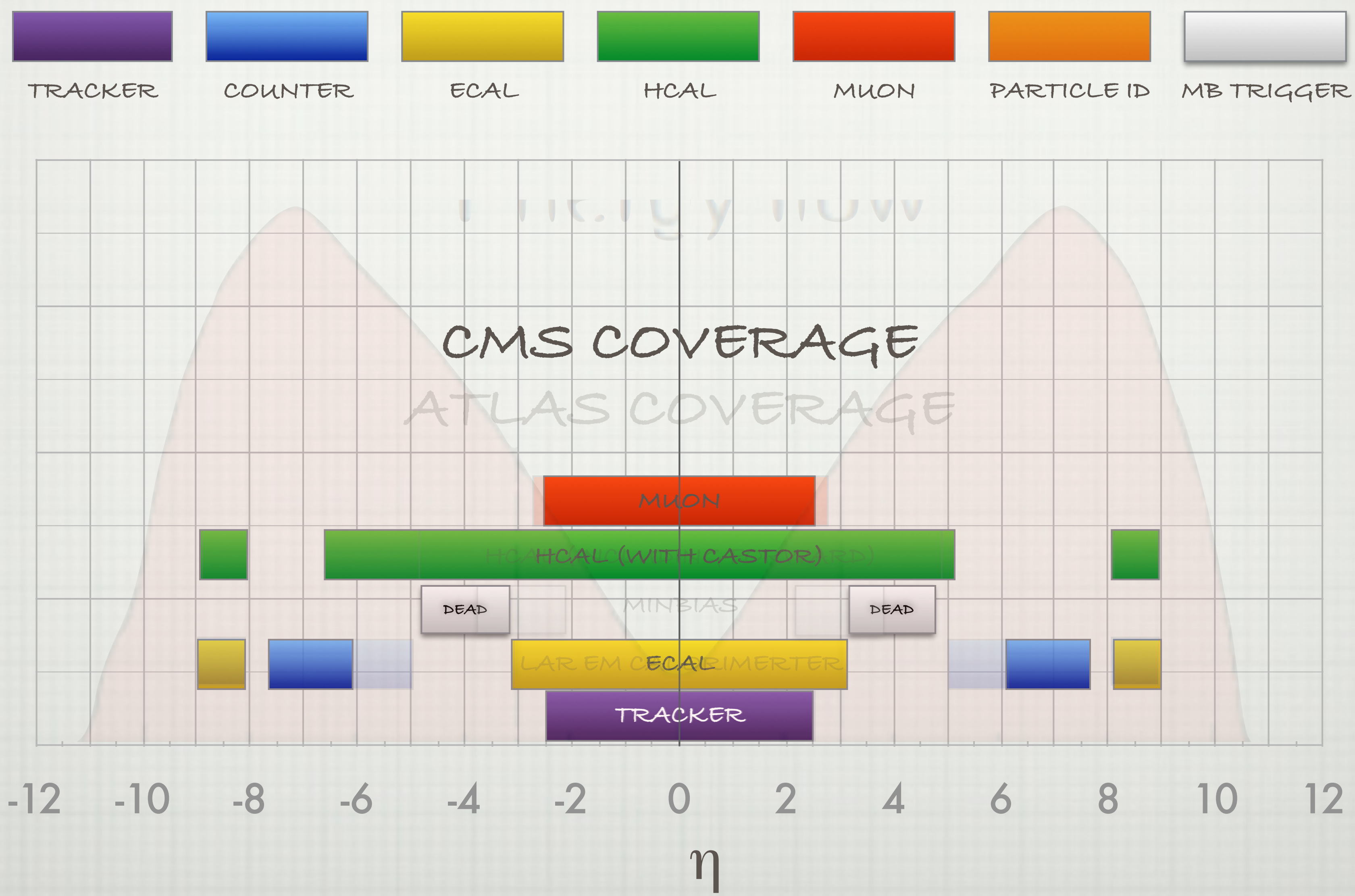

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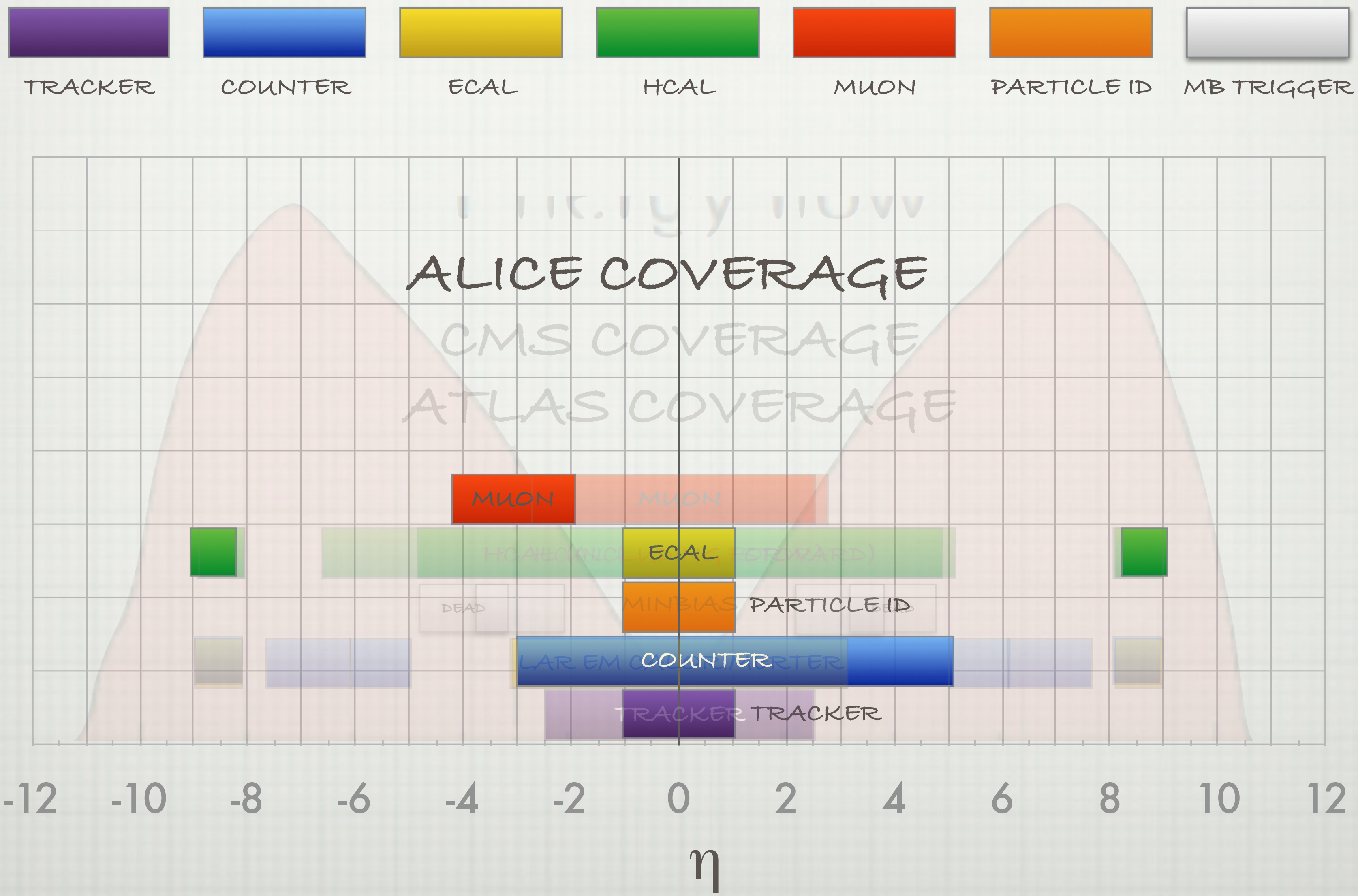

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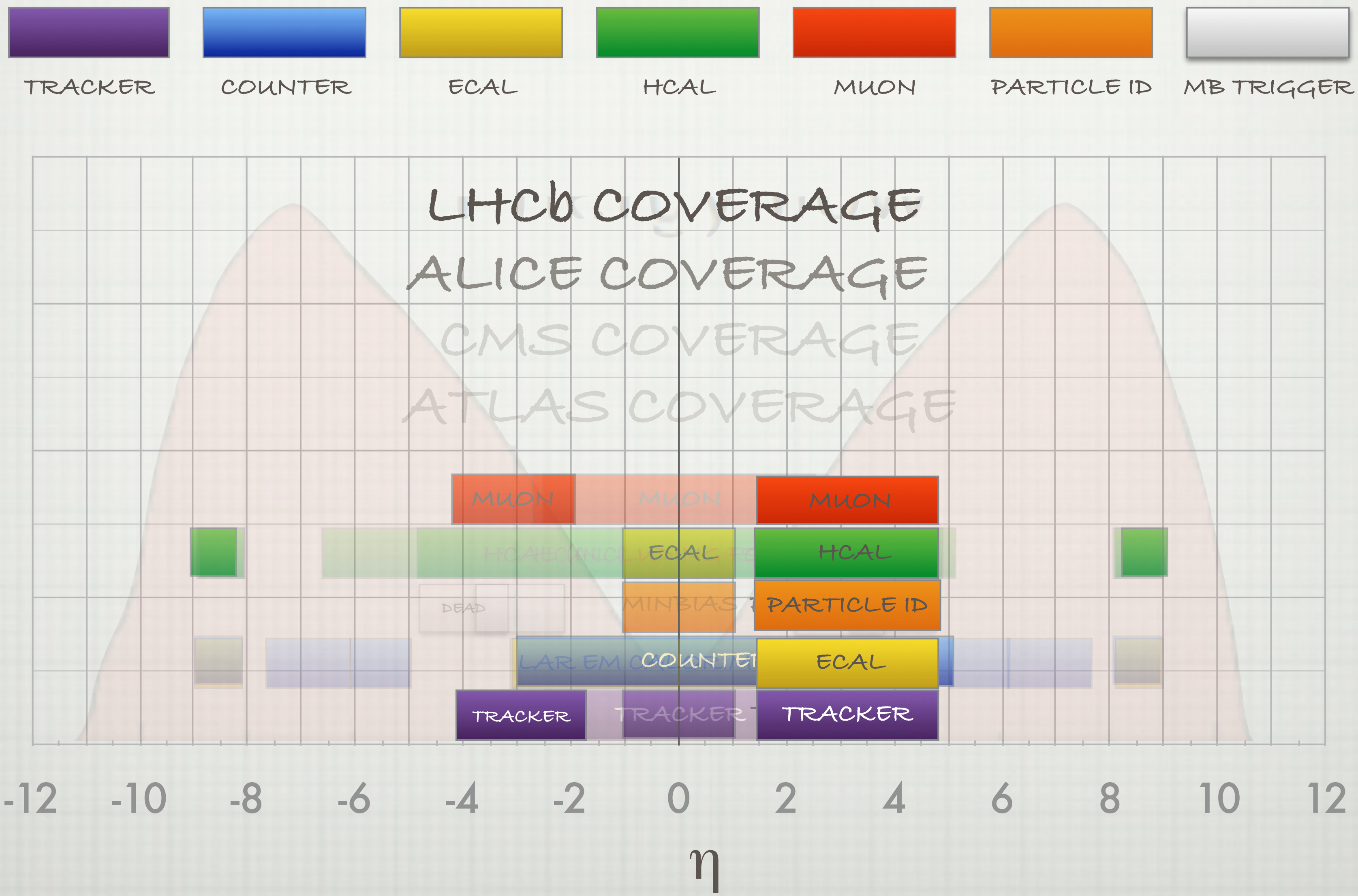

MPI OBSERVABLES

SOFT QCD MPI

- The key plots (both for practical and historical reasons) are:
  - $<p_T>$ vs charged particle multiplicity
  - $dN/d\eta$, dN/dp_T
  - N_{ch} and $\sum p_T$ vs $\Delta\phi$ w.r.t. the object with max(p_T)
- Other, newer observables:
  - Energy flow

$$EF = \frac{1}{N_{int}}\frac{dE_{tot}}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{int}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

CHARGED OR TOTAL

HARD QCD MPI

- Δ^n_{jets} (for W+2j studies with pileup and missing E_T) in ATLAS and CMS

$$\Delta^n_{jets} = \frac{|\vec{p_T}(j_1) + \vec{p_T}(j_2)|}{|\vec{p_T}(j_1)| + |\vec{p_T}(j_2)|}$$

- Δ^{rel}_{soft}, ΔS (for 4-jet studies) in CMS

$$\Delta^{rel}_{soft} p_T = \frac{|\vec{p_T}(\mathbf{j}^{soft_1}) + \vec{p_T}(\mathbf{j}^{soft_2})|}{|\vec{p_T}(\mathbf{j}^{soft_1})| + |\vec{p_T}(\mathbf{j}^{soft_2})|}$$

- ρ' (jet-area)

$$\rho' = \underset{j \in physical\ jets}{median}\left\{\frac{p_{Tj}}{A_j}\right\}\frac{\sum_j A_j}{A_{tot}}$$

$$\Delta S = \frac{|\vec{p_T}(\mathbf{j}^{hard_1,hard_2}) + \vec{p_T}(\mathbf{j}^{soft_1,soft_2})|}{|\vec{p_T}(\mathbf{j}^{hard_1,hard_2})| + |\vec{p_T}(\mathbf{j}^{soft_1,soft_2})|}$$

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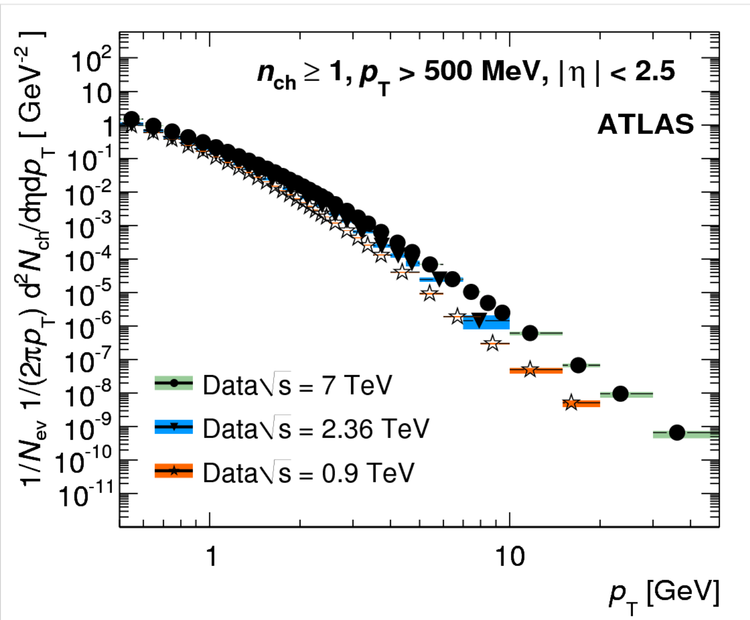
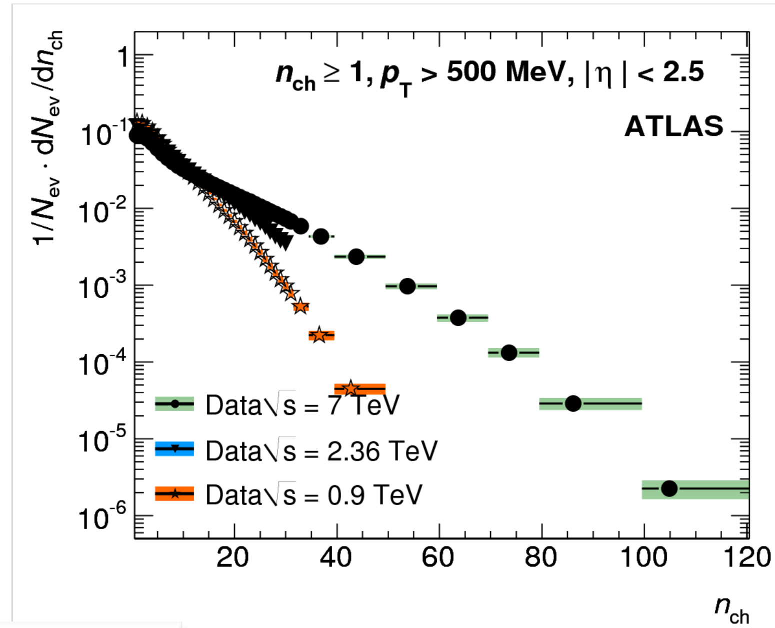
ATLAS CHARGED PARTICLE DATA

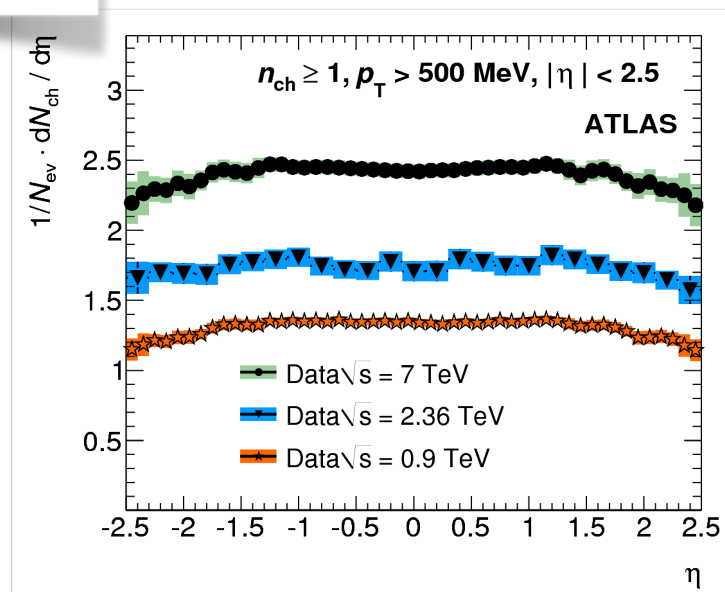


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2010-06/

STANDARD PLOTS, AS MENTIONED BEFORE.



EXPECTED ENERGY EVOLUTION ASSUMING MPI

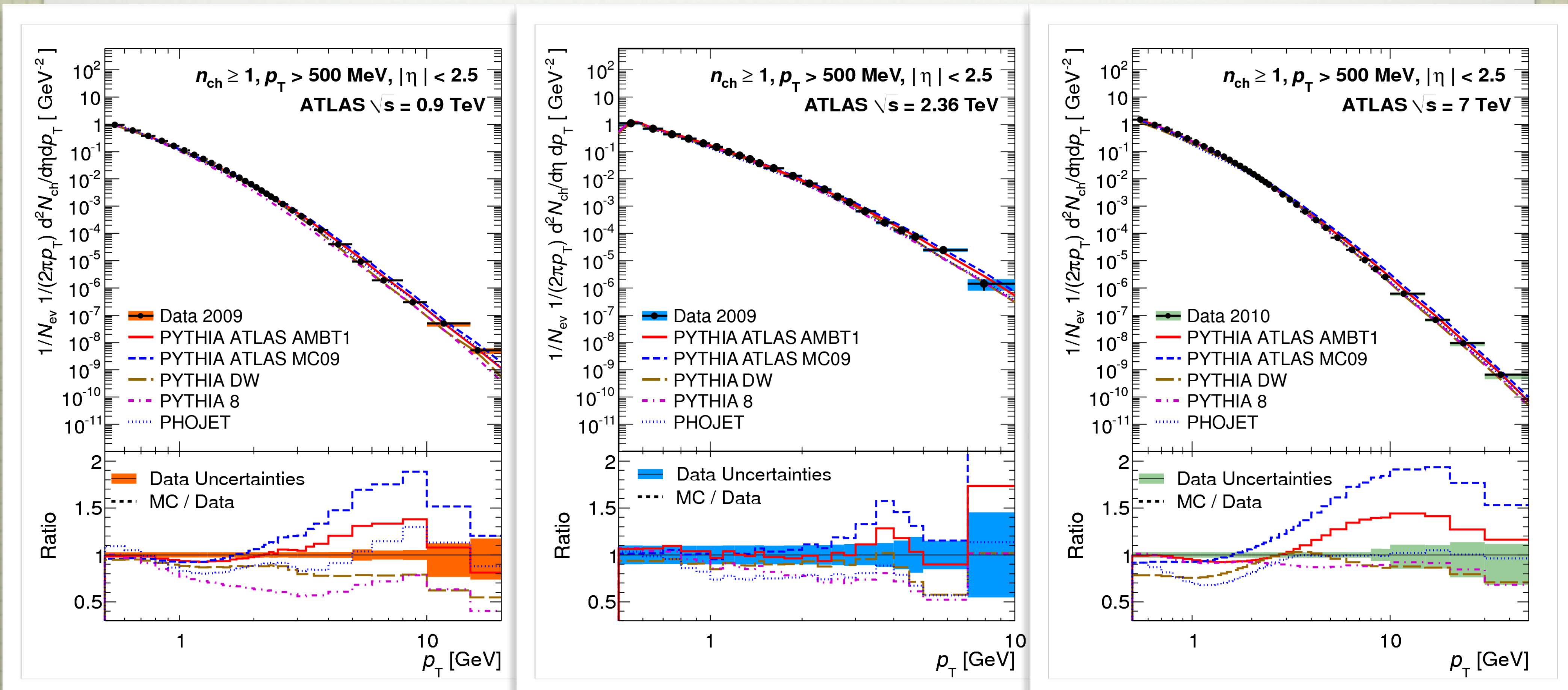


DATA AT √S=0.9, 2.36, AND 7 TEV

ATLAS

CHARGED PARTICLE DENSITY VS p_T

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2010-06/

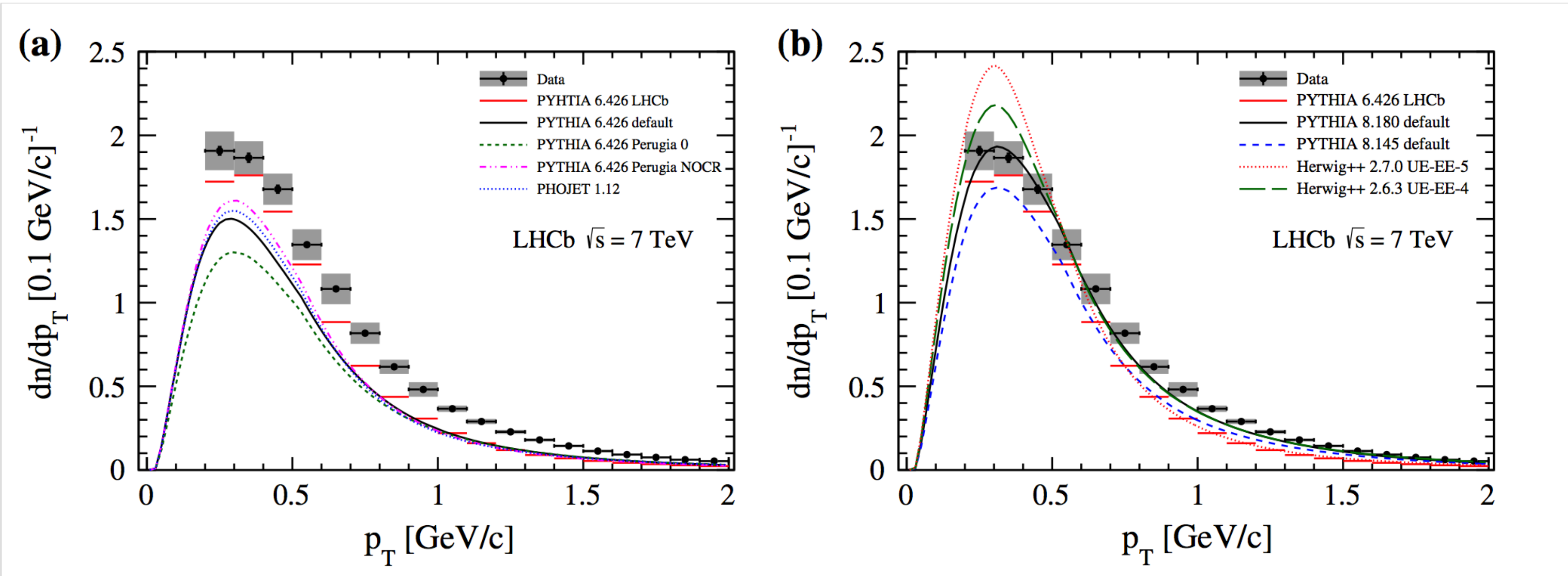


AMBT TUNED FOR 2.36 – PYTHIA 8 IS CLOSEST OVERALL.

HIGH P_T PRESENTS PROBLEMS ACROSS THE BOARD

CHARGED PARTICLE DENSITY VS p_T

http://arxiv.org/abs/1402.4430



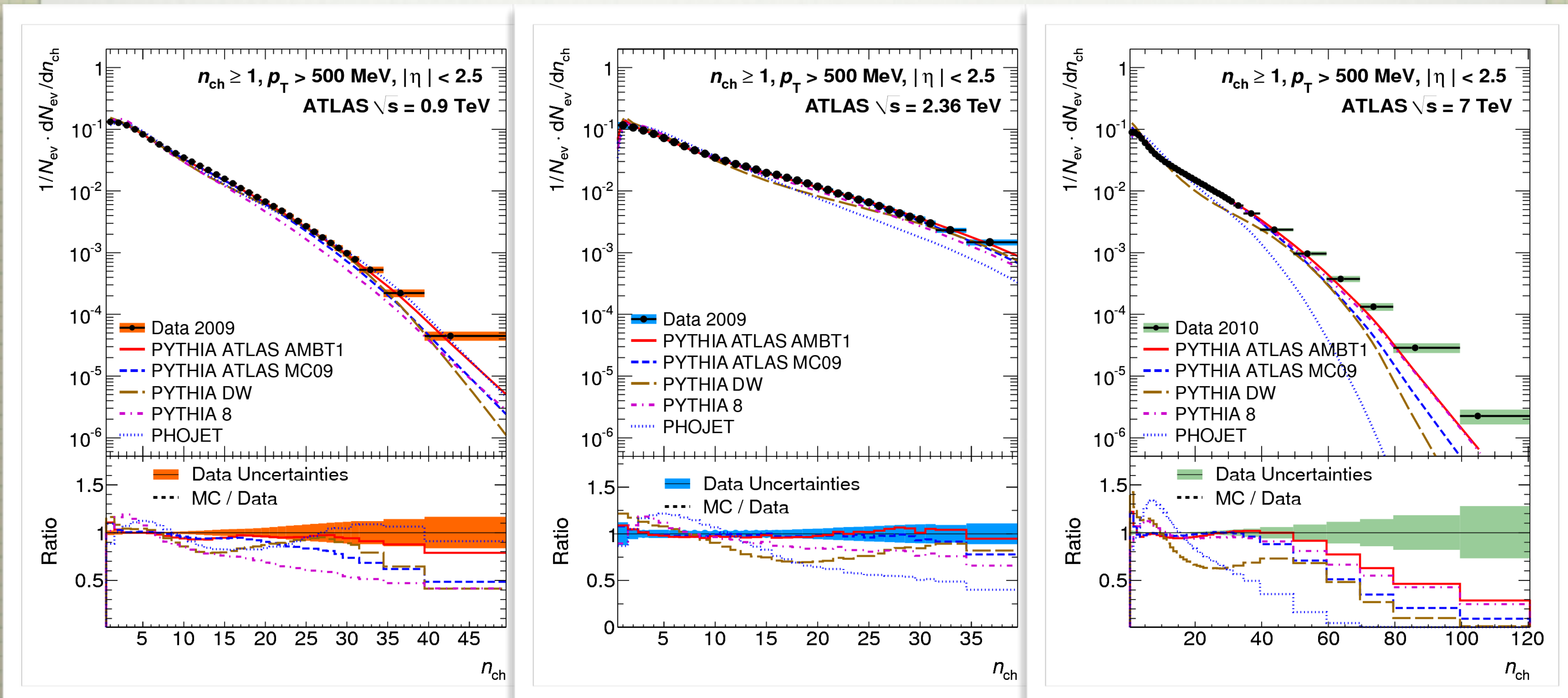
PYTHIA 8.180 IS THE CLOSEST, GOOD FIT

VERY FORWARD PARTICLES

LHCb

CHARGED PARTICLE MULTIPLICITY

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2010-06/



ALL UNDERSHOOT DRAMATICALLY AT 7 TEV,

BUT AMBT BEST OVER ALL CM ENERGIES.

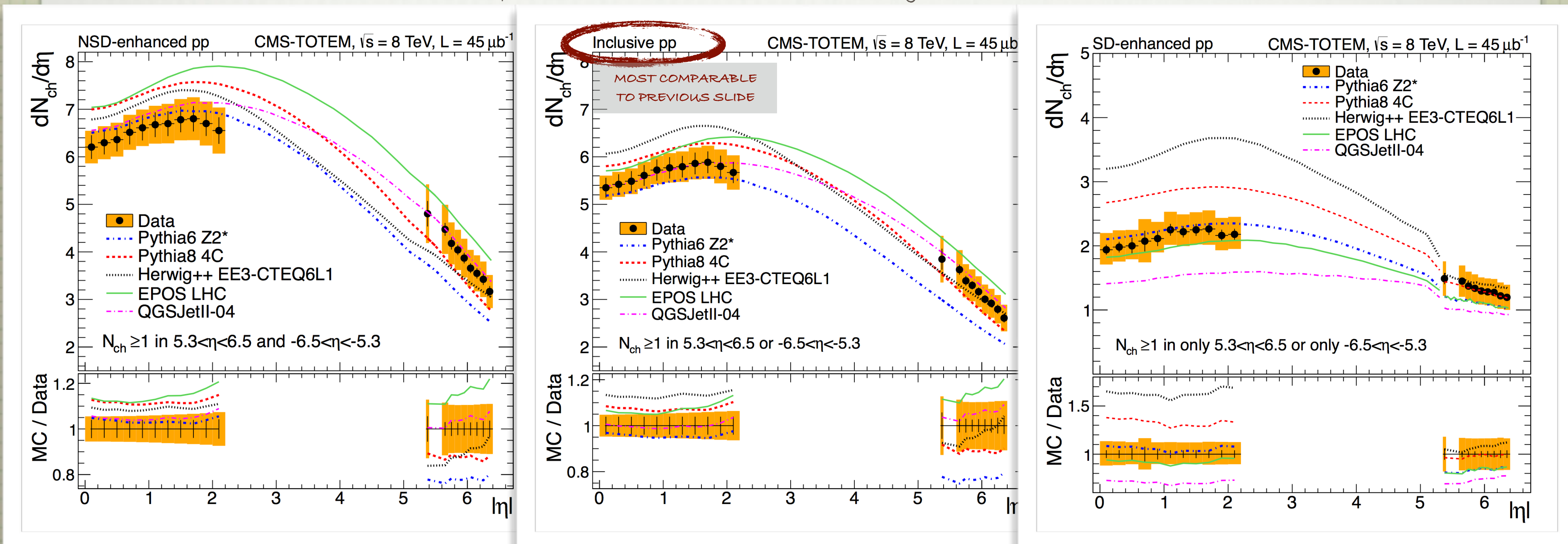
IS THERE AN ENERGY DEPENDENCE LIKE CMS SAW?

(NEXT SLIDE)

ATLAS

CMS/TOTEM CHARGED PARTICLE DENSITY VS. ETA

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ12026

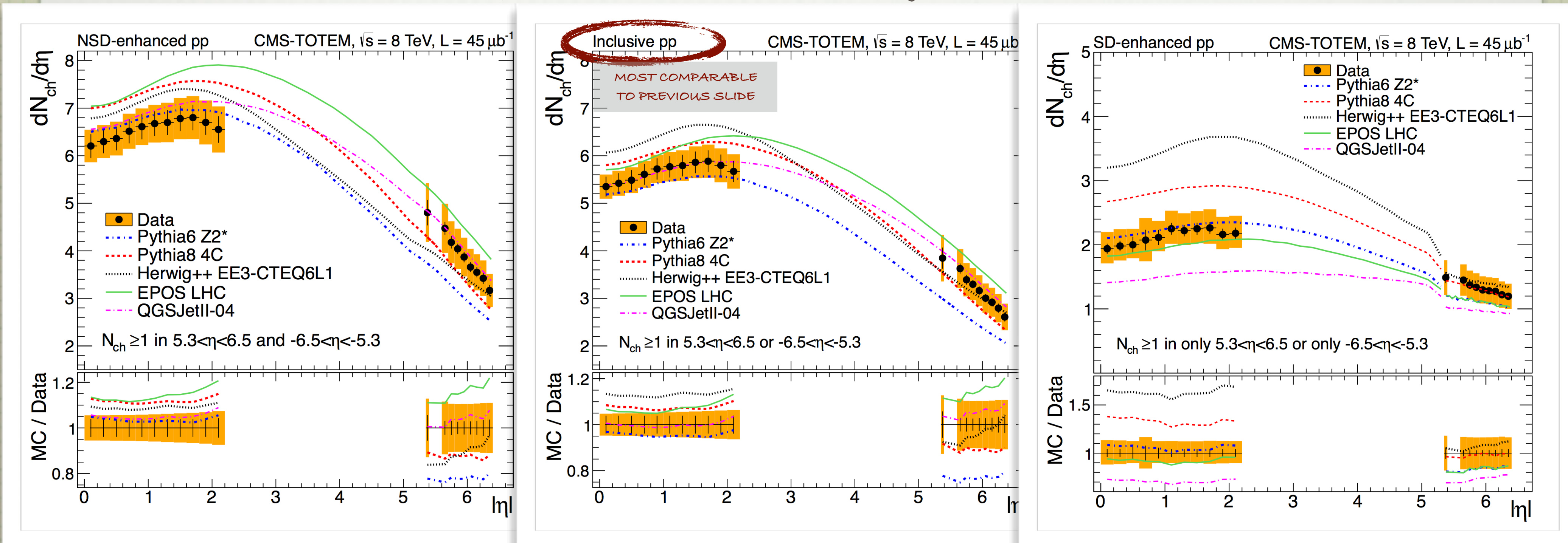


INTERESTING IN COMPARISON TO ATLAS:
PY8 OVERSHOOTS AND PY6 UNDERSHOOTS,
WHERE IN ATLAS BOTH ARE UNDER.

CMS

CMS/TOTEM CHARGED PARTICLE DENSITY VS. ETA

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ12026

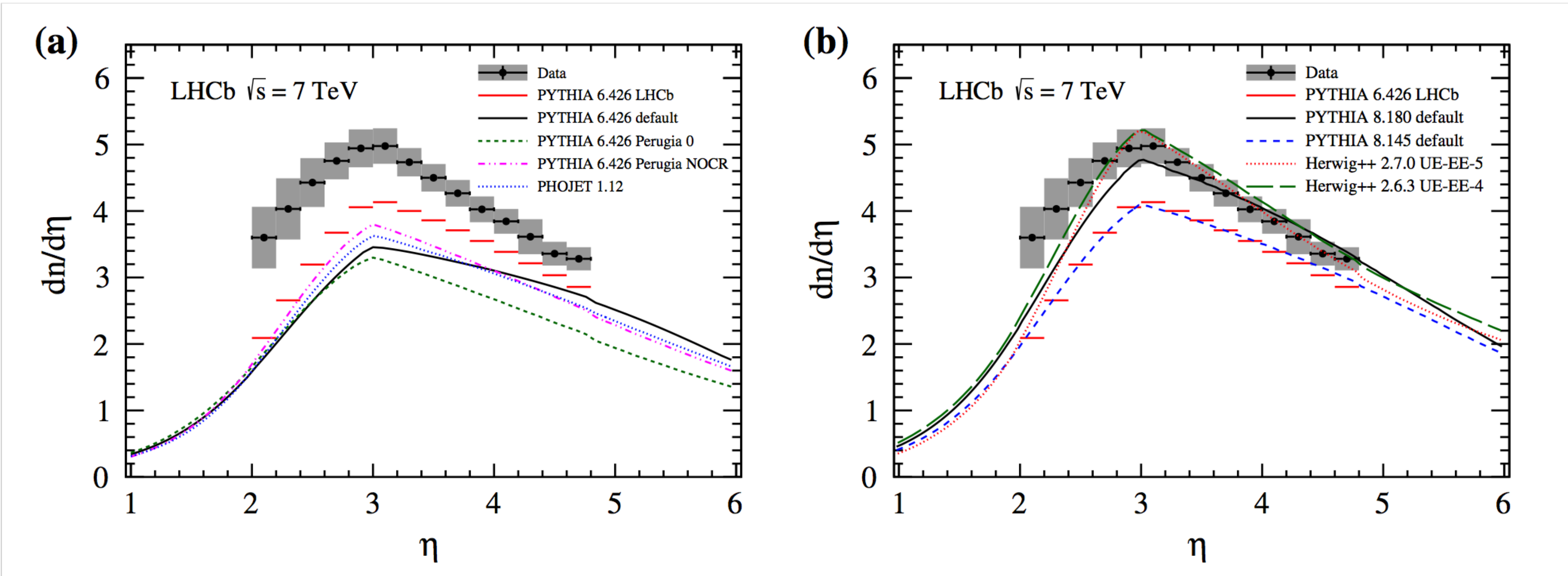


NOTE HOW THE NEXT SLIDE (LHCb) OVERLAYS THE GAP AREA — A GREAT POTENTIAL FOR COMBINED RESULTS

CMS

CHARGED PARTICLE DENSITIES AS A FUNCTION OF η

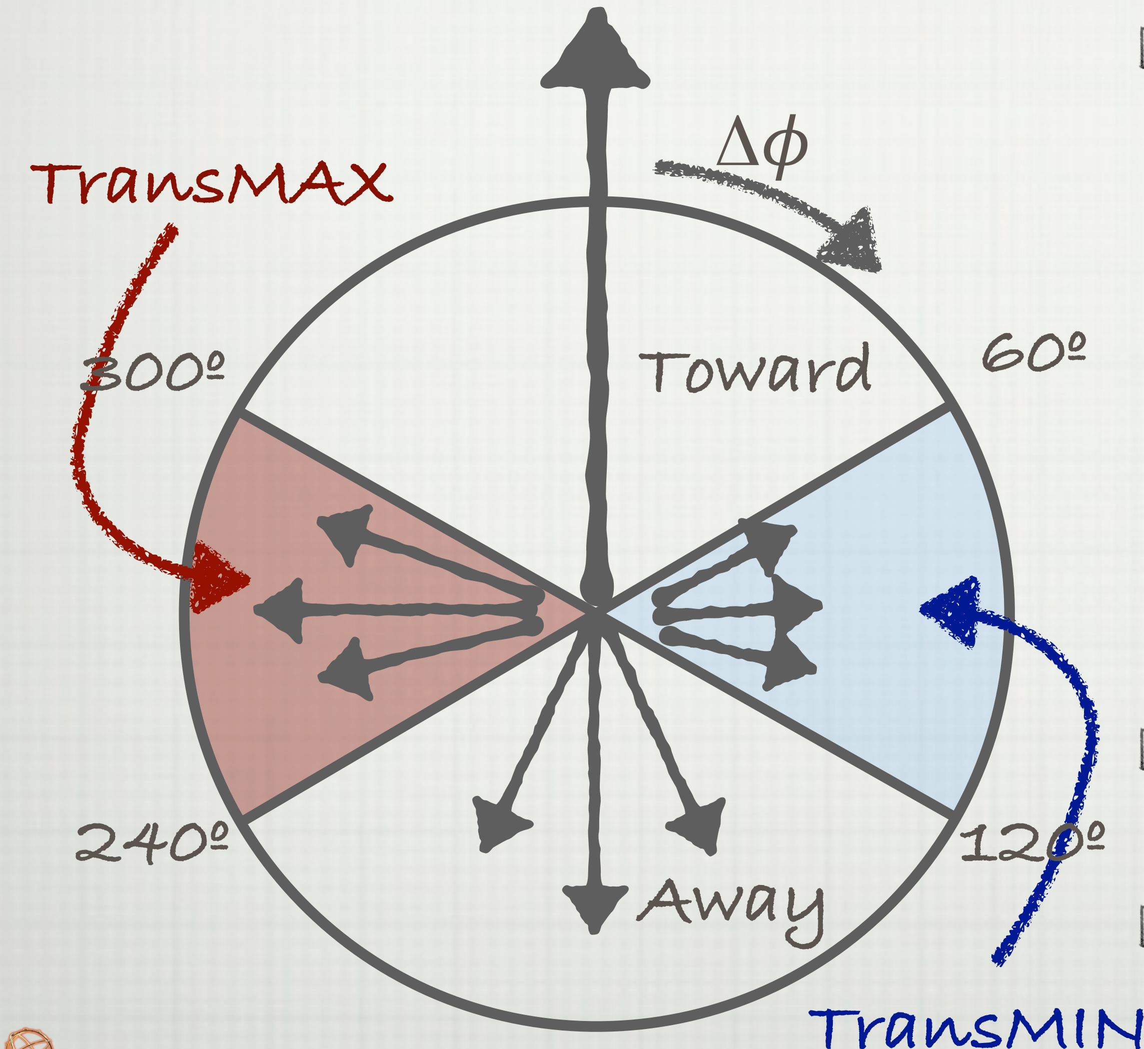
http://arxiv.org/abs/1402.4430



CLEAN WIN HERE FOR THE HERWIG++ VERSIONS, THOUGH THEY OVERSHOOT AT LOW η. CONSISTENT WITH THE CMS RESULTS, PREVIOUS.

LHCb

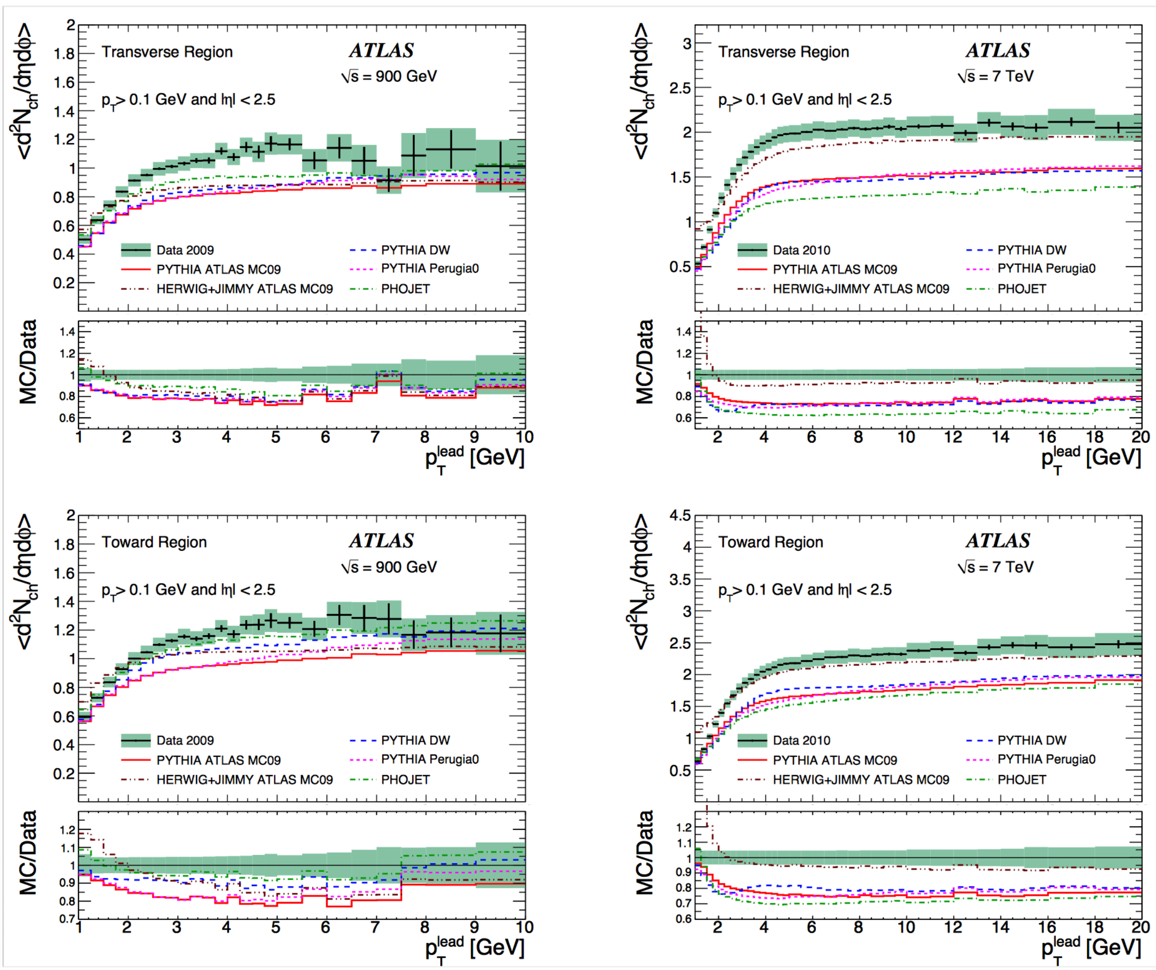
TRANSMIN/TRANSMAX

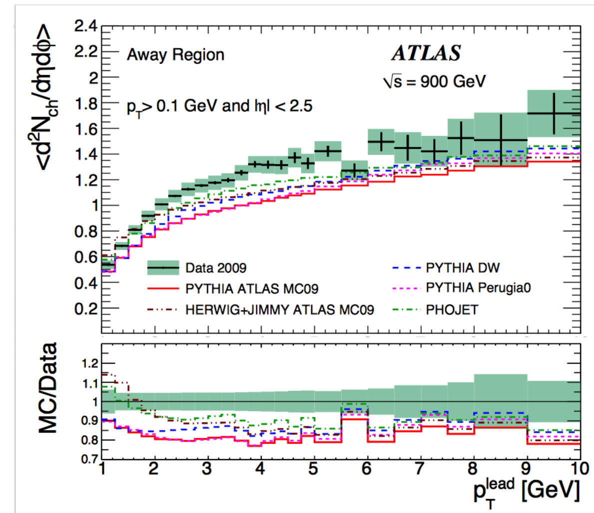


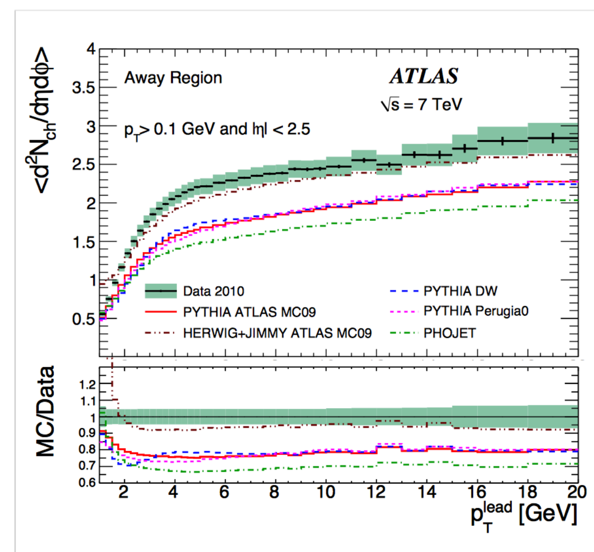
- The next few observables are discussed in terms of
  - Toward
  - Away
  - transMIN
  - transMAX
    - transDIFF
- Enhances observable's sensitivity to MPI
- Leading (highest p_T) object defines coordinates

CHARGED PARTICLE DENSITY VS $P_{T_{LEADING}}$

http://arxiv.org/pdf/1012.0791v2.pdf

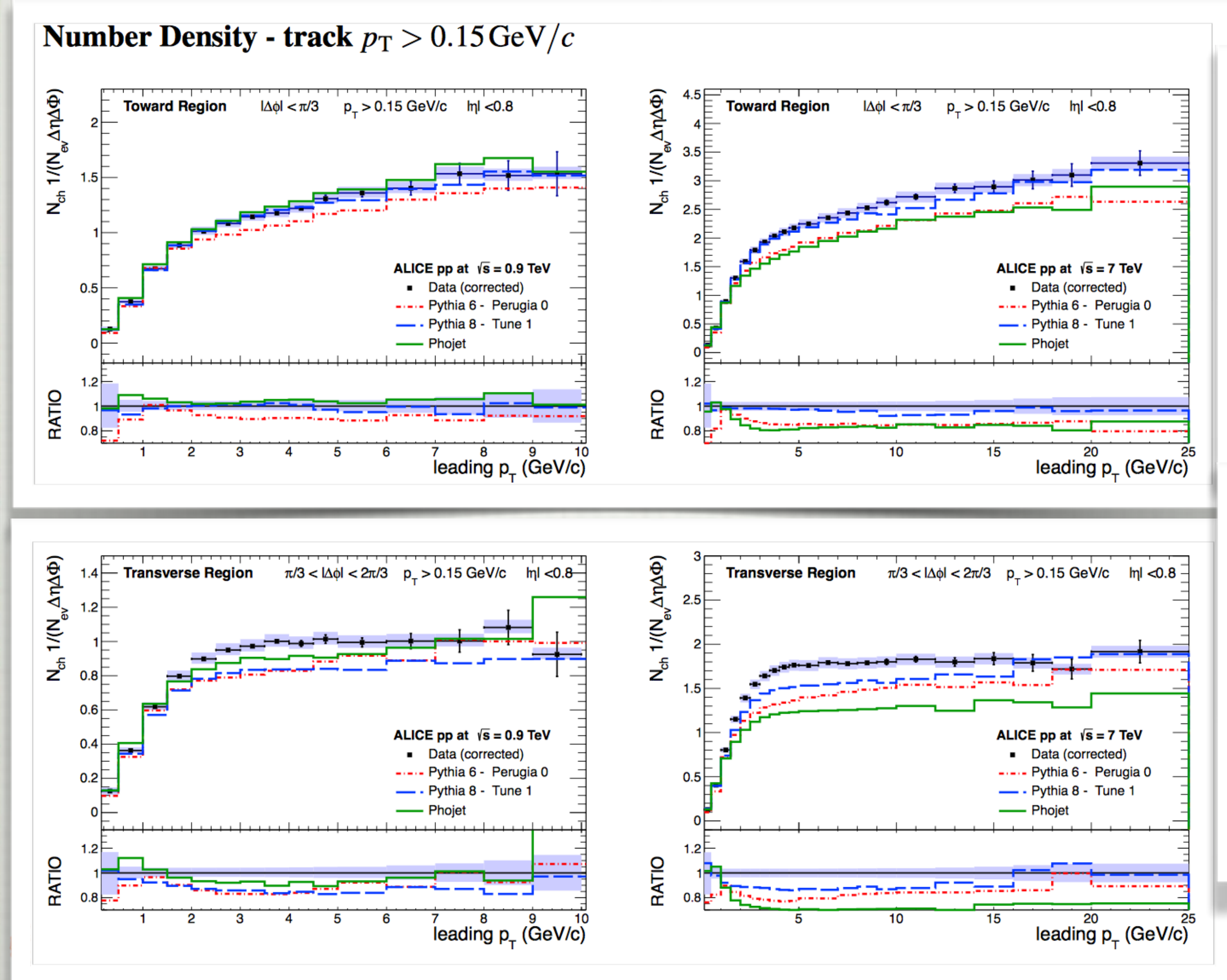


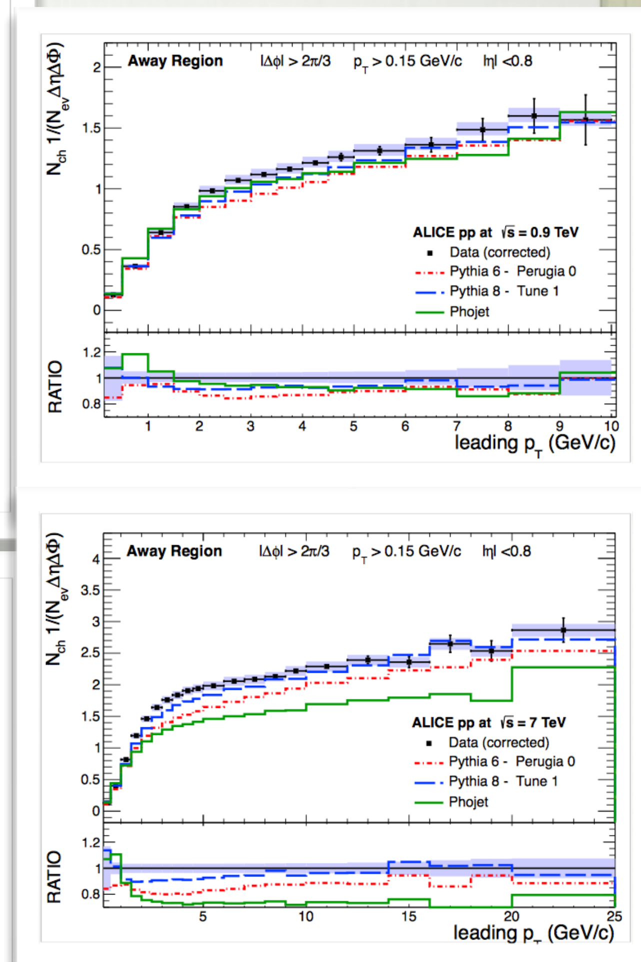




ALICE NUMBER DENSITY

http://arxiv.org/pdf/1112.2082v3.pdf





NEWER OBSERVABLES

- ENERGY FLOW
- $<\sum P_T>$ AND $<N_{CH}>$ VS
  - LEADING P_T
  - MULTIPLICITY
- Z/JET COMPARISONS
- JET AREA

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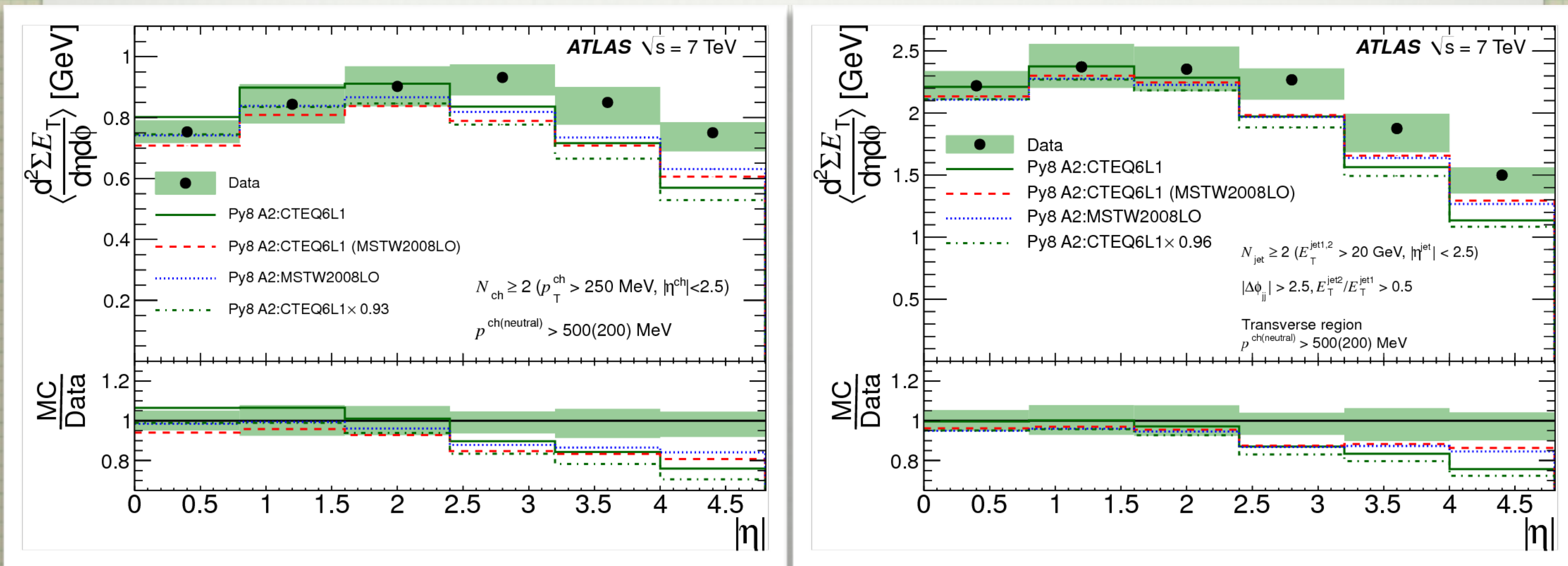
CHARGED PARTICLE ENERGY FLOW

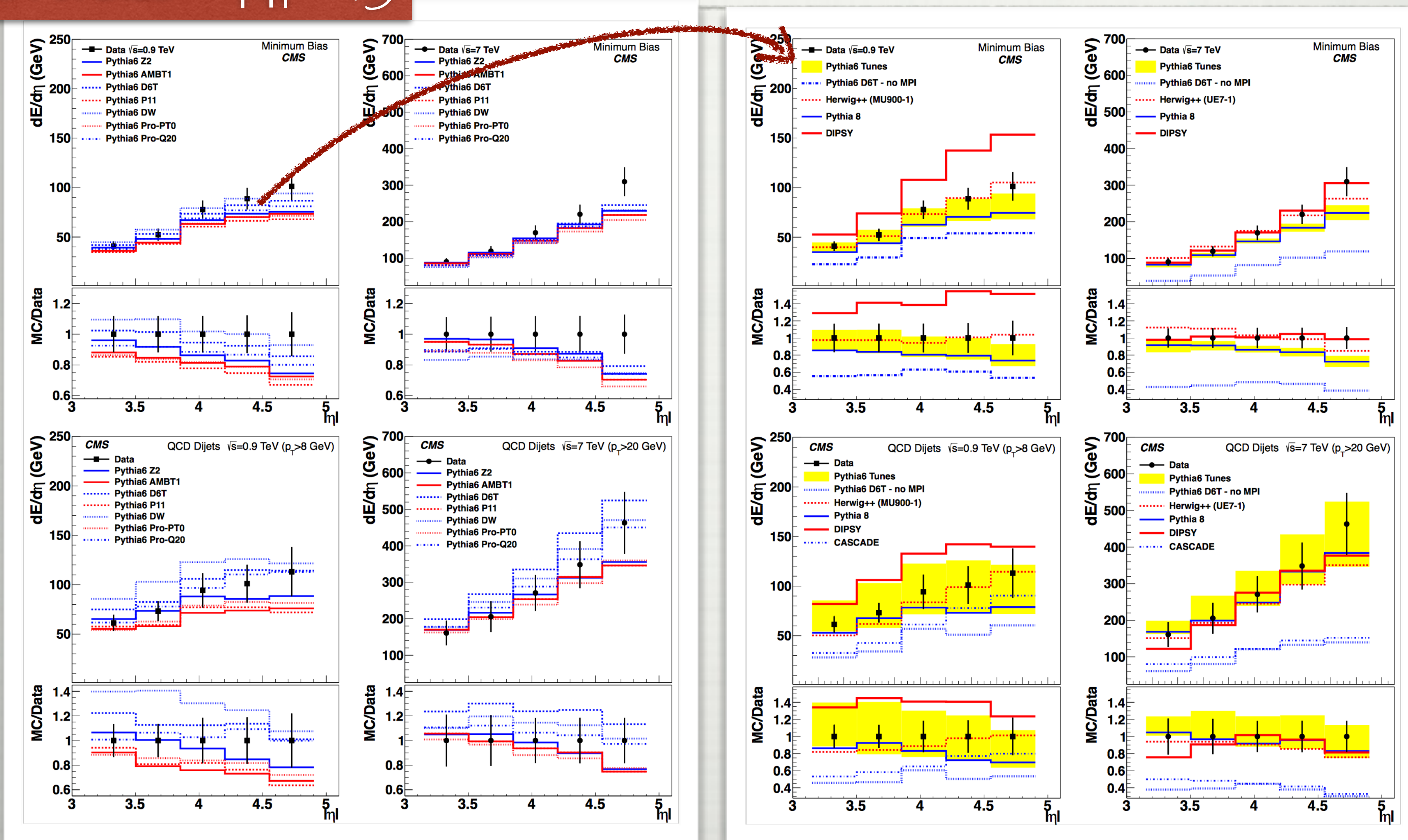
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-44/



CMS ENERGY FLOW

NOTE: $3.15 < |\eta| < 4.9$

http://arxiv.org/pdf/1110.0211v1.pdf



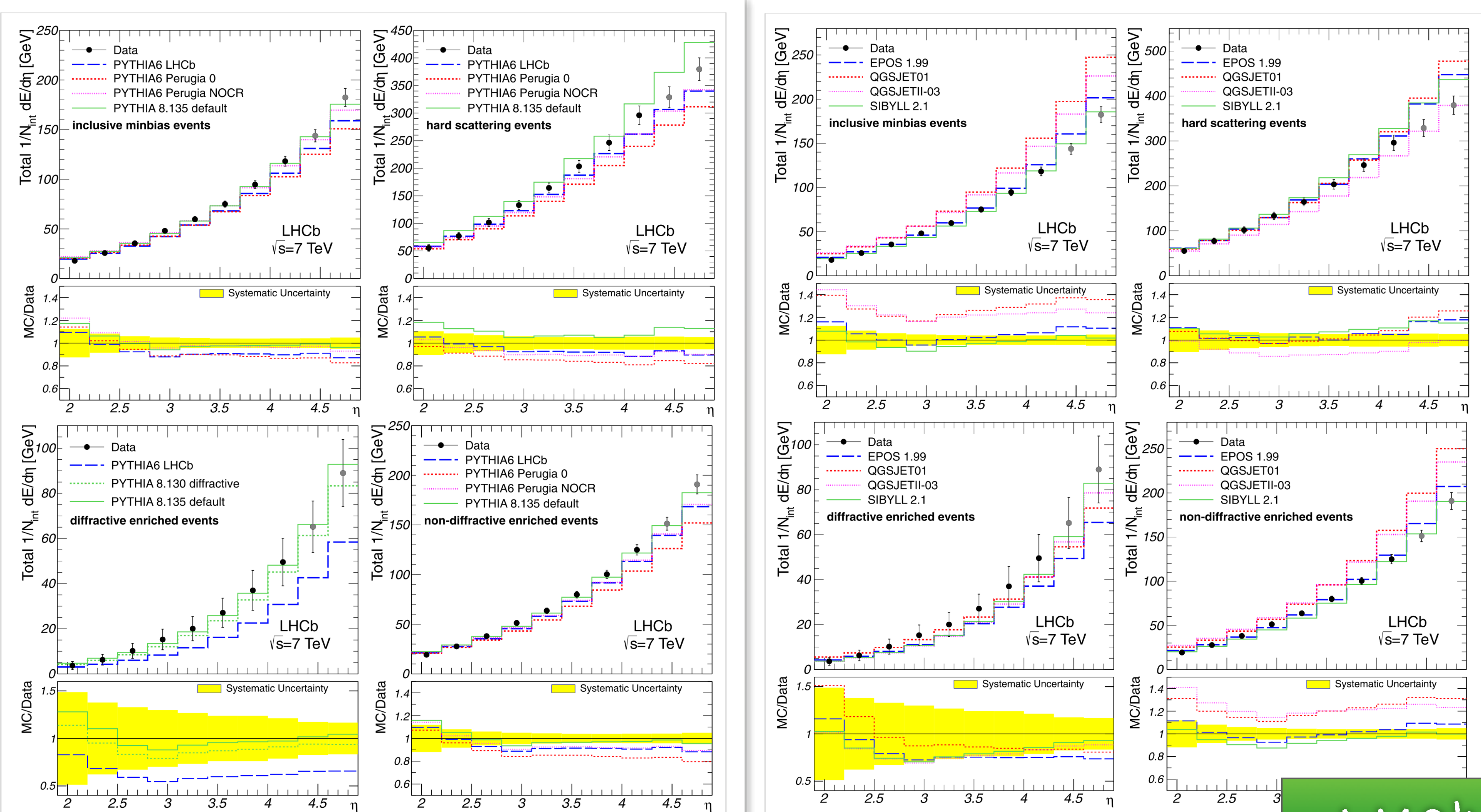
COSMICS GENERATORS HERE:

CMS

TOTAL ENERGY FLOW

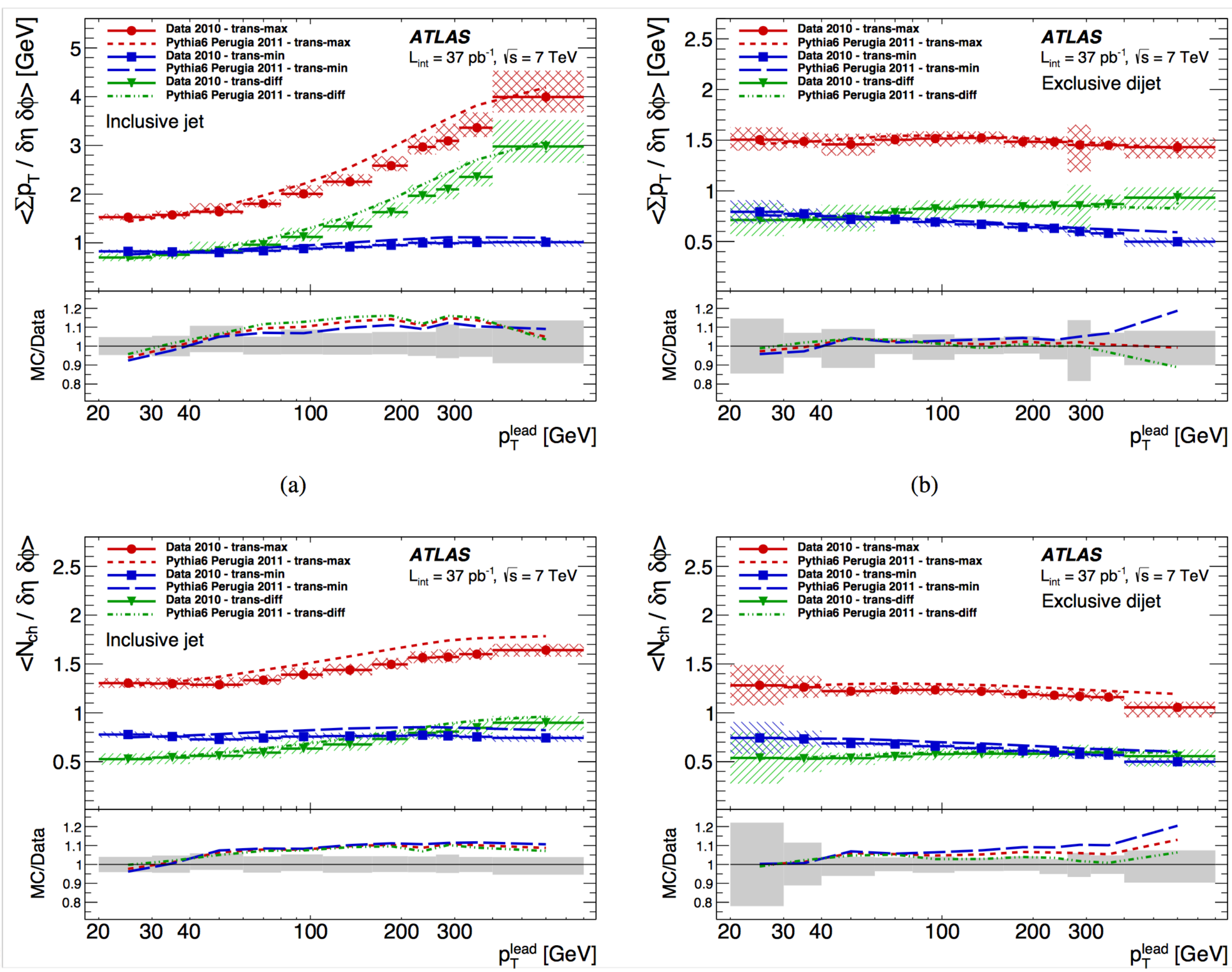
$$EF = \frac{1}{N_{int}}\frac{dE_{tot}}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{int}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

HTTP://ARXIV.ORG/ABS/1212.4755



$\langle\sum P_T\rangle$ AND $\langle N_{ch}\rangle$ VS LEADING JET P_T (INCLUSIVE JET, EXCLUSIVE DIJET)

http://arxiv.org/abs/1406.0392

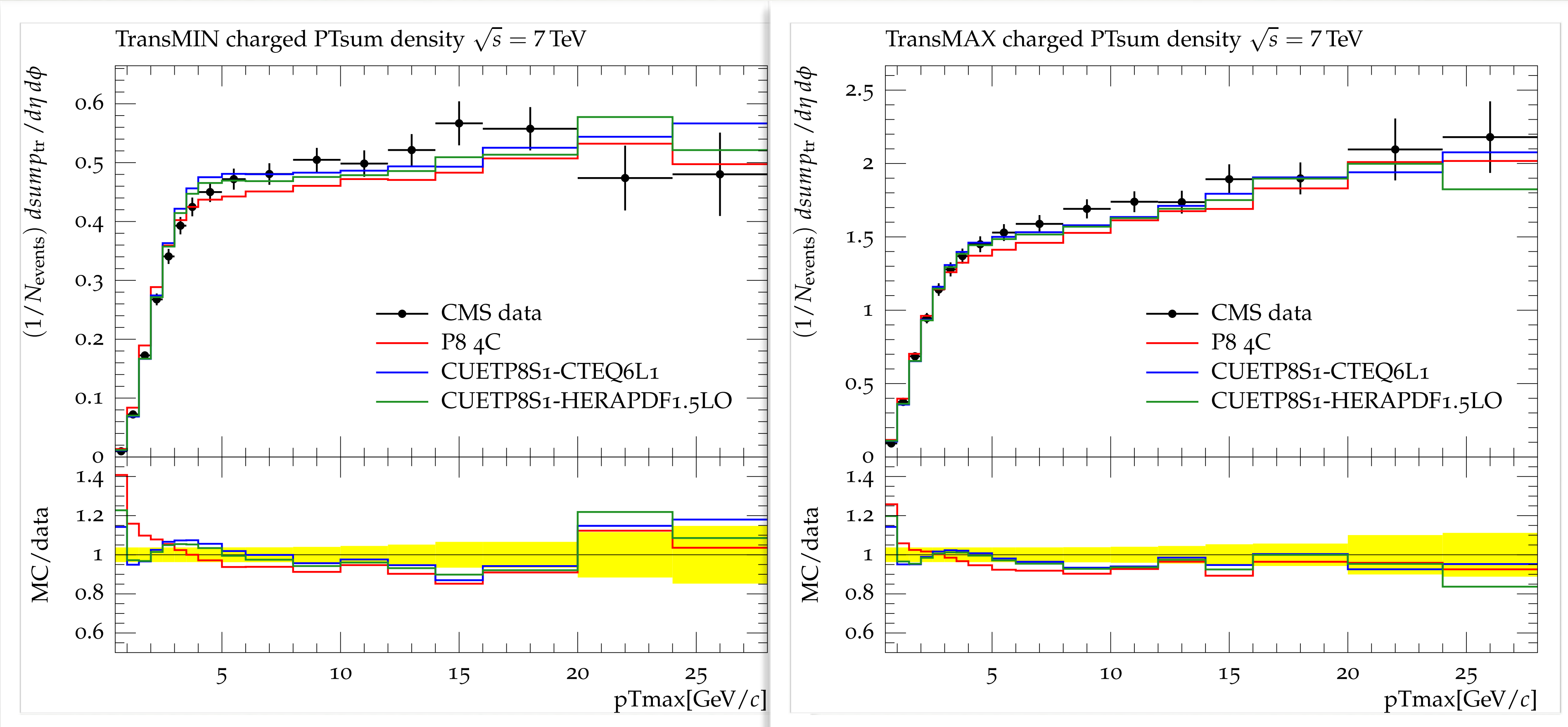


Notable: this illustrates neatly the usefulness of the transMIN/ transMAX/ transDIFF observables.

MORE GENERATORS HERE:

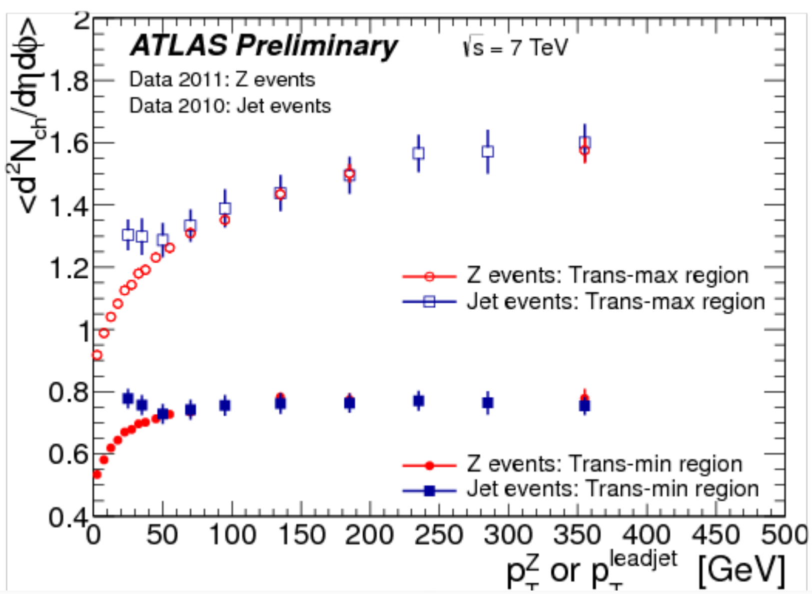
<∑PT> VS LEADING JET PT

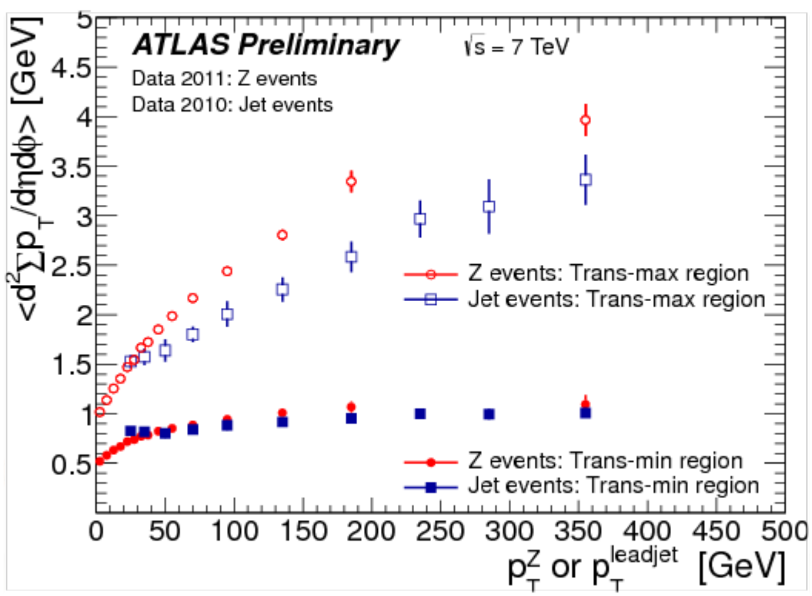
https://cds.cern.ch/record/1697700?ln=en

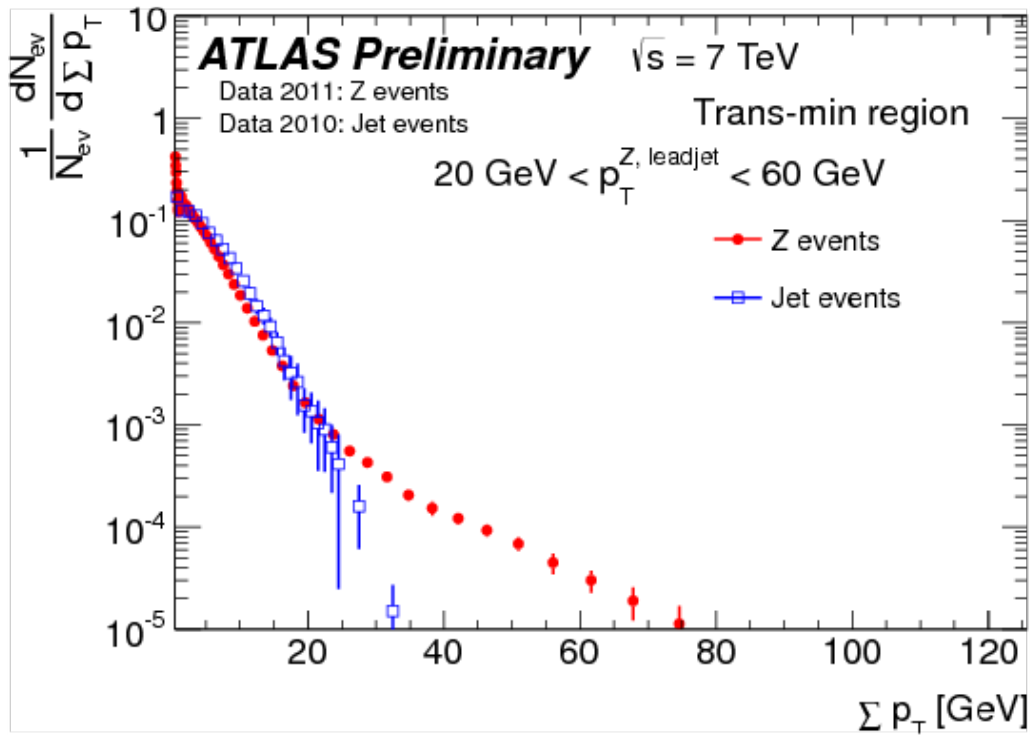


UPCOMING... INCLUSIVE Z EVTS.

(PRELIMINARY)





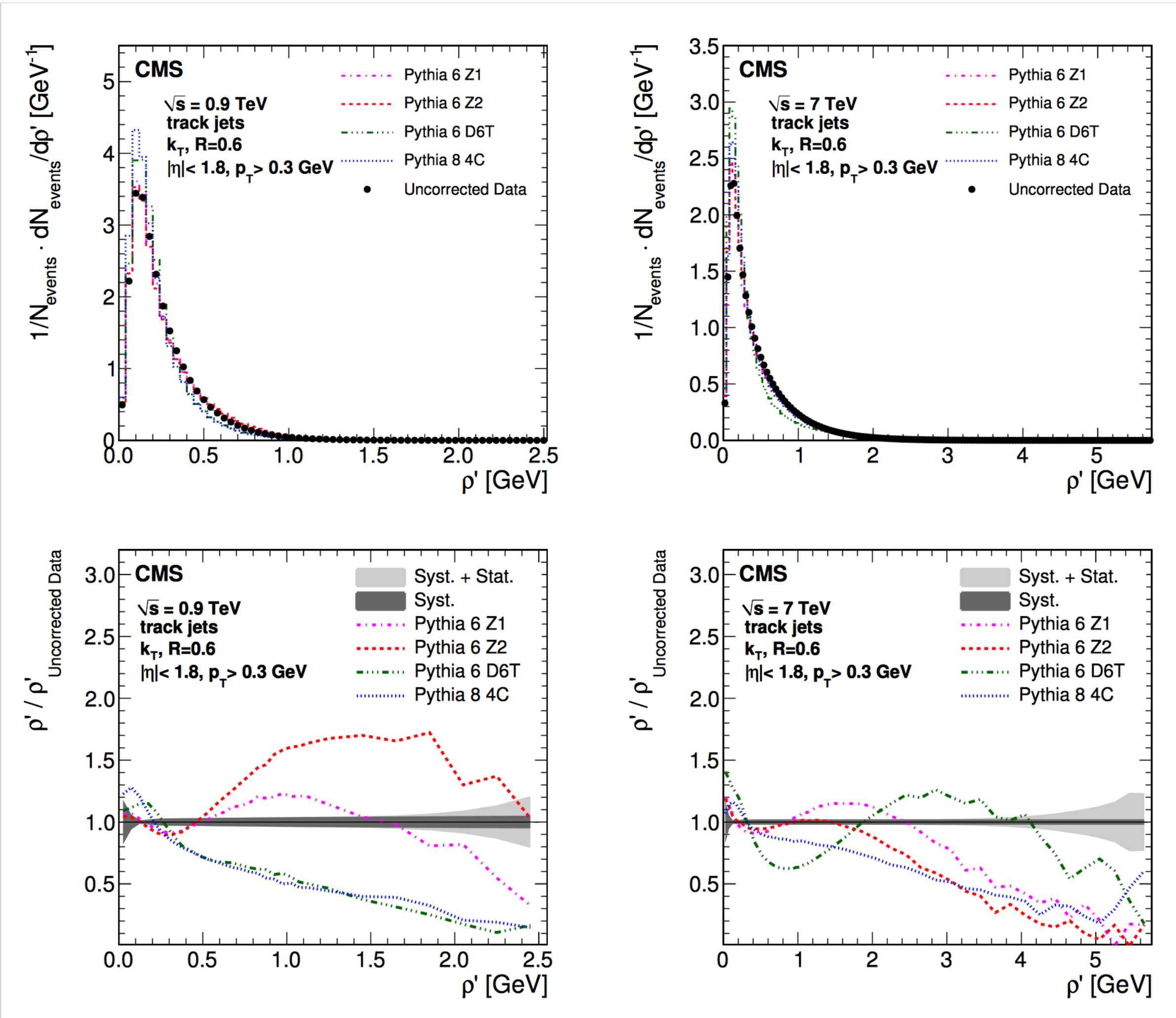


https://indico.desy.de/getFile.py/access?contribId=31&sessionId=15&resId=0&materialId=slides&confId=9319

ATLAS

JET AREA/MEDIAN

http://arxiv.org/abs/1207.2392



$$\rho' = \underset{j \in physical\ jets}{median} \left\{ \frac{p_{Tj}}{A_j} \right\} \frac{\sum_j A_j}{A_{tot}}$$

CMS

CONCLUSIONS

- MPI in the soft regime can indeed be recognized and added
  - But the generator(s)/tune/PDF cocktail that you use will be customized to the observables you are examining
- Some convergence between experiments in one or two observables...
  - But others are clearly still disconnected
  - Extremes of p_T and η are still disconnected from more central values in the description

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CONCLUSIONS (CONT.)

- Innovative observables may extend the search into high-pileup/high-pT searches,
  - W+2j, Z, 4j events, etc.
    - Or at least increase sensitivity to failings in the simulation
- It seems (to me) like there are real and fundamental subtleties with the model that need to be worked out.
- 14 TeV tunings underway based on 7 and 8 TeV tunings, using automated tuning systems to test and discard adjustments, exploring the solution surface.

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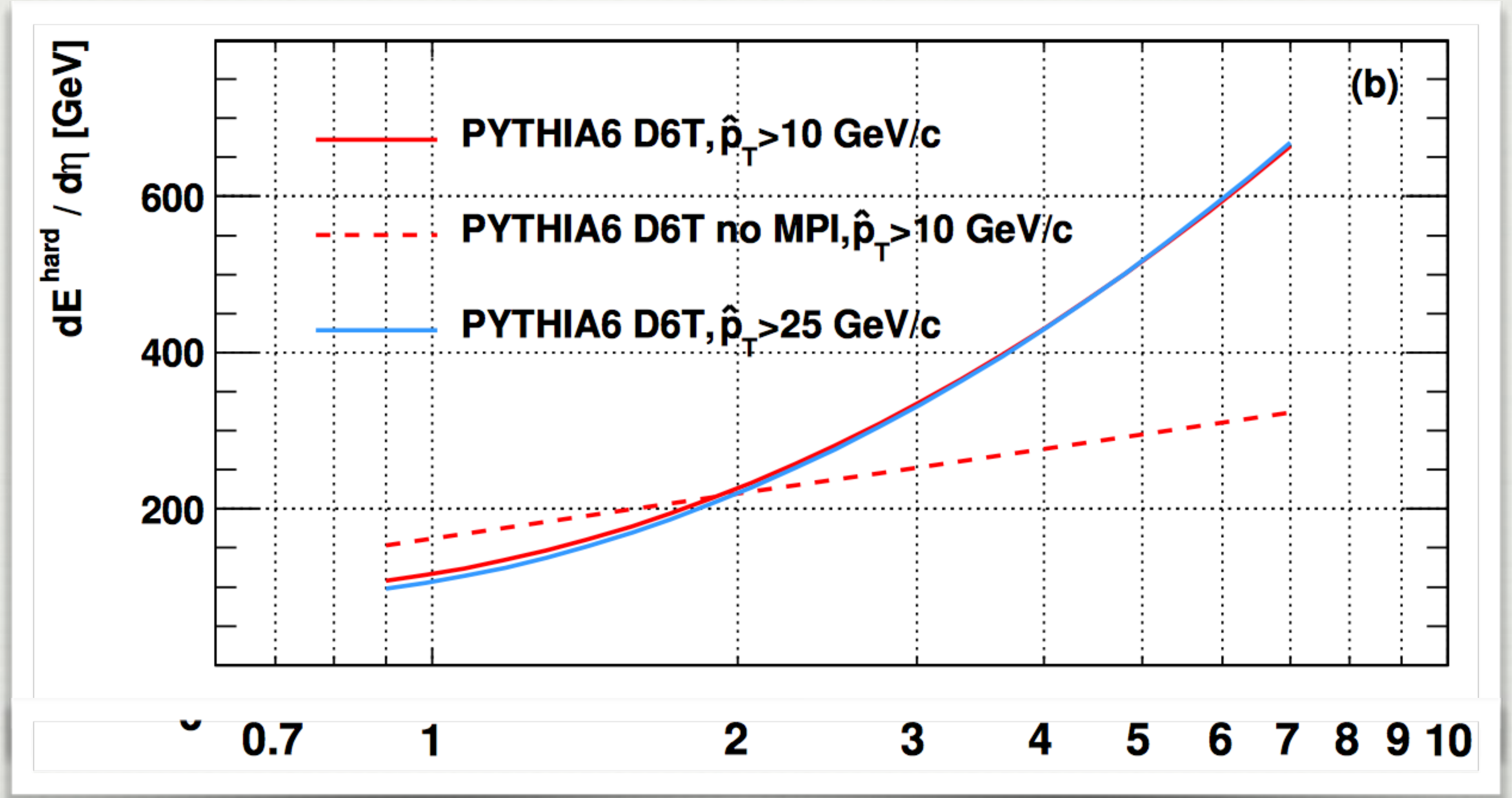
BACKUP

IMPORTANCE OF MPI



GENERATOR DISCUSSIONS (PYTHIA 6.4)

Tune	PDF	Experiment
Perugia NOCR	CTEQ5L	ATLAS, LHCb
Perugia 0	CTEQ5L	ATLAS, CMS, LHCb, ALICE
Perugia 0 No MPI	CTEQ5L	LHCb
LHCb	CTEQ6L	LHCb
D6T	CTEQ6L1	CMS
PROQ20	CTEQ5L	CMS
DW	CTEQ5L	ATLAS, CMS
CUETP6S1	CTEQ6L1	CMS (recent)
Z1	CTEQ5L1	CMS
Z2	CTEQ6L1	CMS (older)
AMBT1	MRST2007LO	ATLAS
AUET2B	CTEQ6L1	ATLAS

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GENERATOR DISCUSSIONS (PYTHIA 8.1)

Tune	PDF	Experiment
Default 8.130	CTEQ5L	LHCb, ATLAS, CMS
Default 8.135	CTEQ6L1	LHCb, ATLAS, CMS
4C	CTEQ6L1	ATLAS, CMS
A2:CTEQ6L1	CTEQ6L1	ATLAS
A2:MSTW2008 LO	MSTW2008 LO	ATLAS
CUETP8S1	CTEQ6L1	CMS
CUETP8S1	CTEQ6L1	CMS
Monash/8.183	NNPDF 2.3 LO	ATLAS, CMS?

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GENERATOR DISCUSSIONS OTHER HEP AND COSMICS

Generator	Notes	Experiment
Herwig++	MRST LO	ATLAS, CMS, LHCb
HERWIG/JIMMY	JIMMY handles MPI	ATLAS
ALPGEN	MPI for hard processes	ATLAS
EPOS	Cosmics, LHC Tune	ATLAS, CMS, LHCb
QSGJET01	Cosmics	LHCb, CMS
QSGJETII-03,04	Cosmics	LHCb, CMS
SIBYLL 2.1	Cosmics, LHC Tune	LHCb, CMS
CASCADE	No MPI	CMS
DIPSY	BFKL	CMS

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INTRO AND HEADLINERS (CONTINUED)

- Monte Carlo (MC) descriptions of LHC p-p collisions without MPI undershoot key parameters by a significant amount:
  - Charged particle multiplicities, η distributions, and probabilities
  - Forward energy flow (neutral and charged)
- Evaluate existing MC
  - Hand optimizations for one observable confounds other tunings.
  - The tuning for an observable in one final state fails in another
    - Aided by iterative or automatic tuning? (more on that later)
  - Problems in models? In PDFs? Multitude of generators to try.

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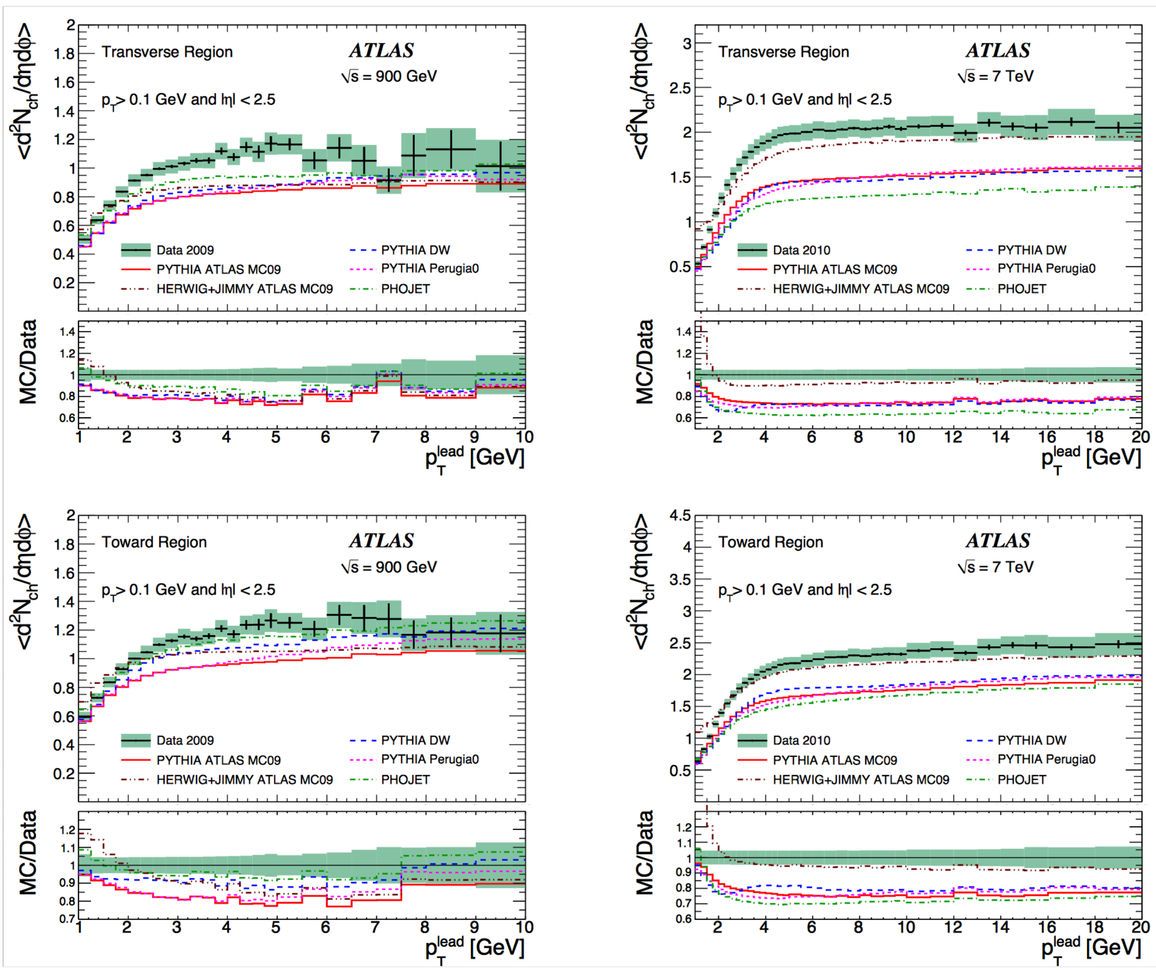
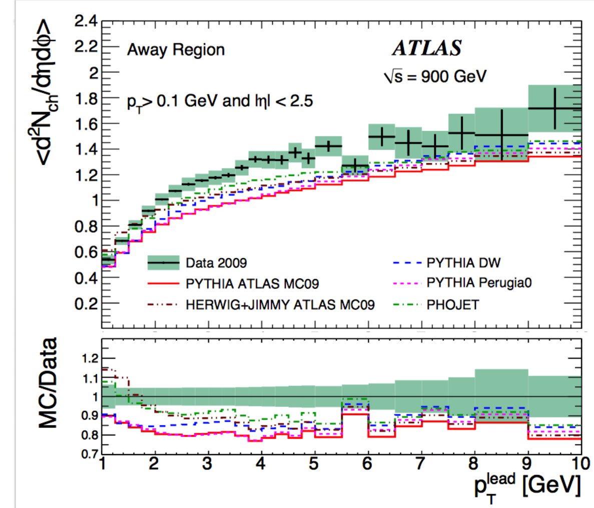
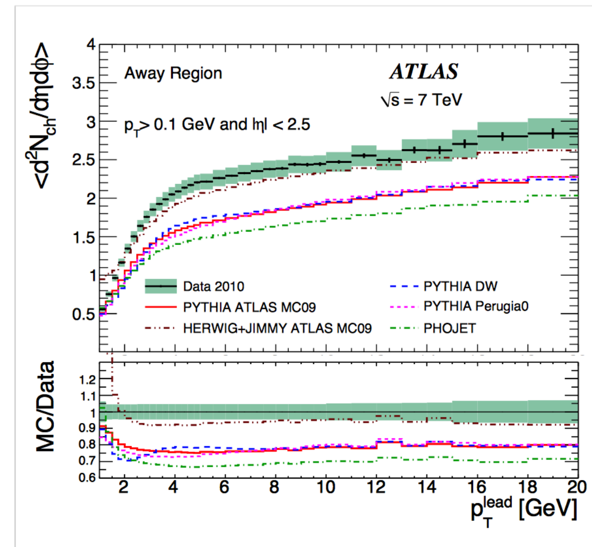
CHARGED PARTICLE DENSITY VS P_{T} LEADING

http://arxiv.org/pdf/1012.0791v2.pdf



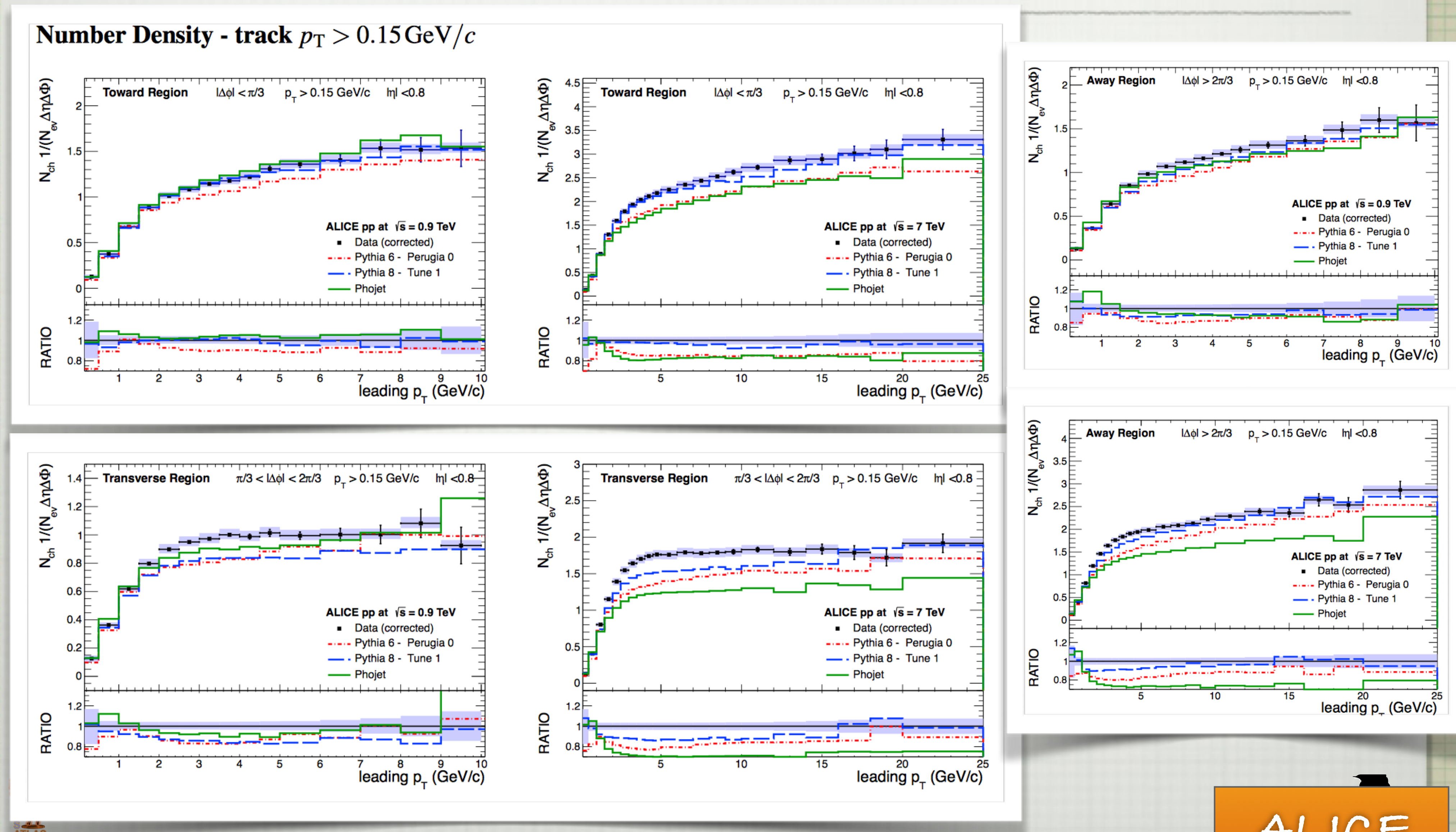




ATLAS

ALICE NUMBER DENSITY

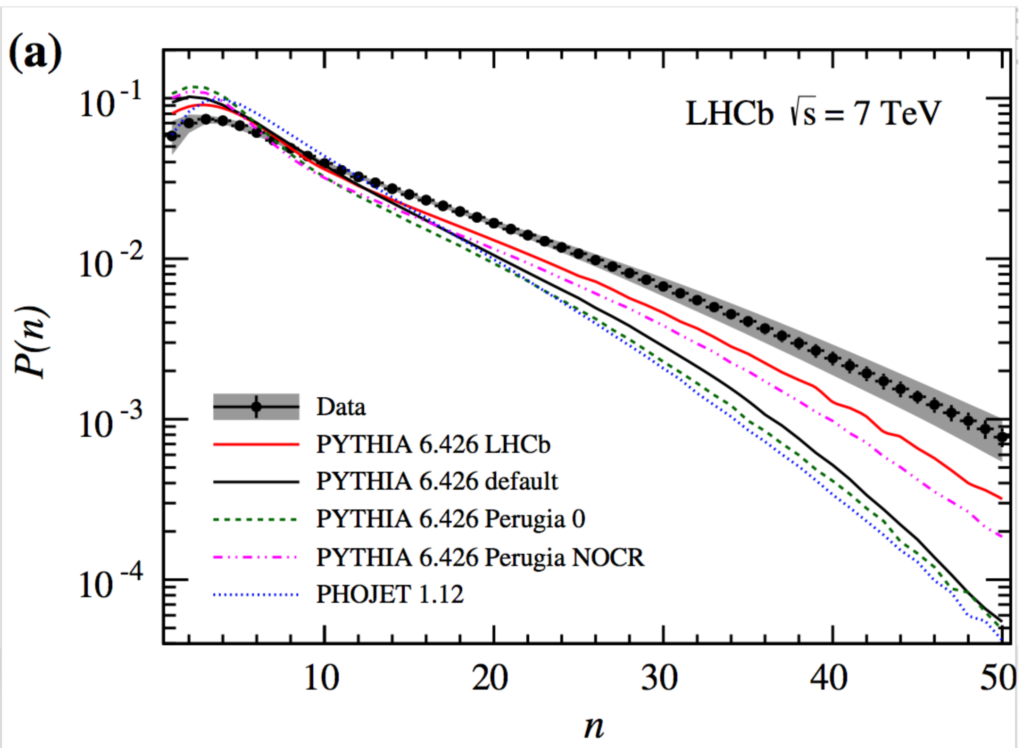
http://arxiv.org/pdf/1112.2082v3.pdf

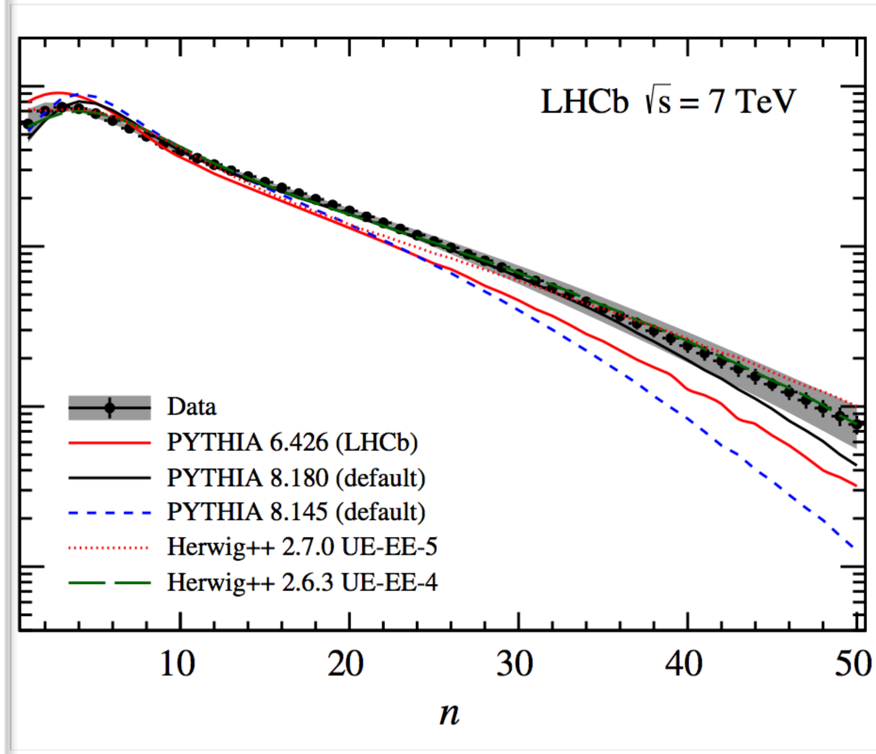


ALICE

CHARGED PARTICLE DENSITY

http://arxiv.org/pdf/1402.4430v2.pdf



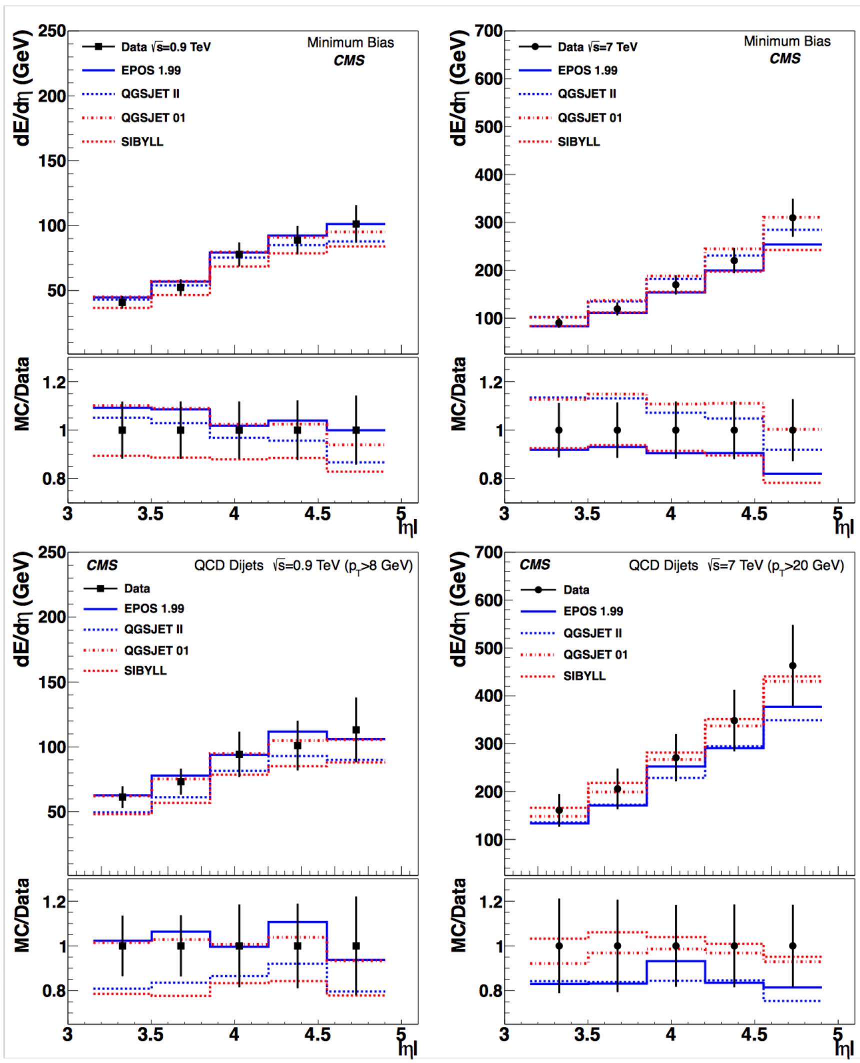


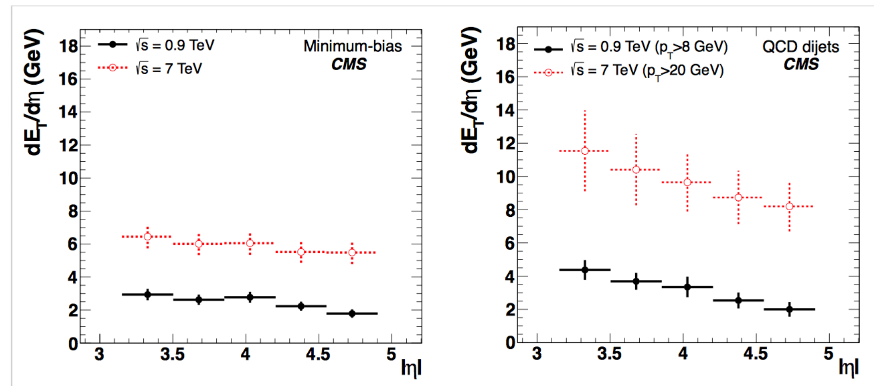
LHCb

CMS ENERGY FLOW

NOTE: 3.15 < |η| <4.9

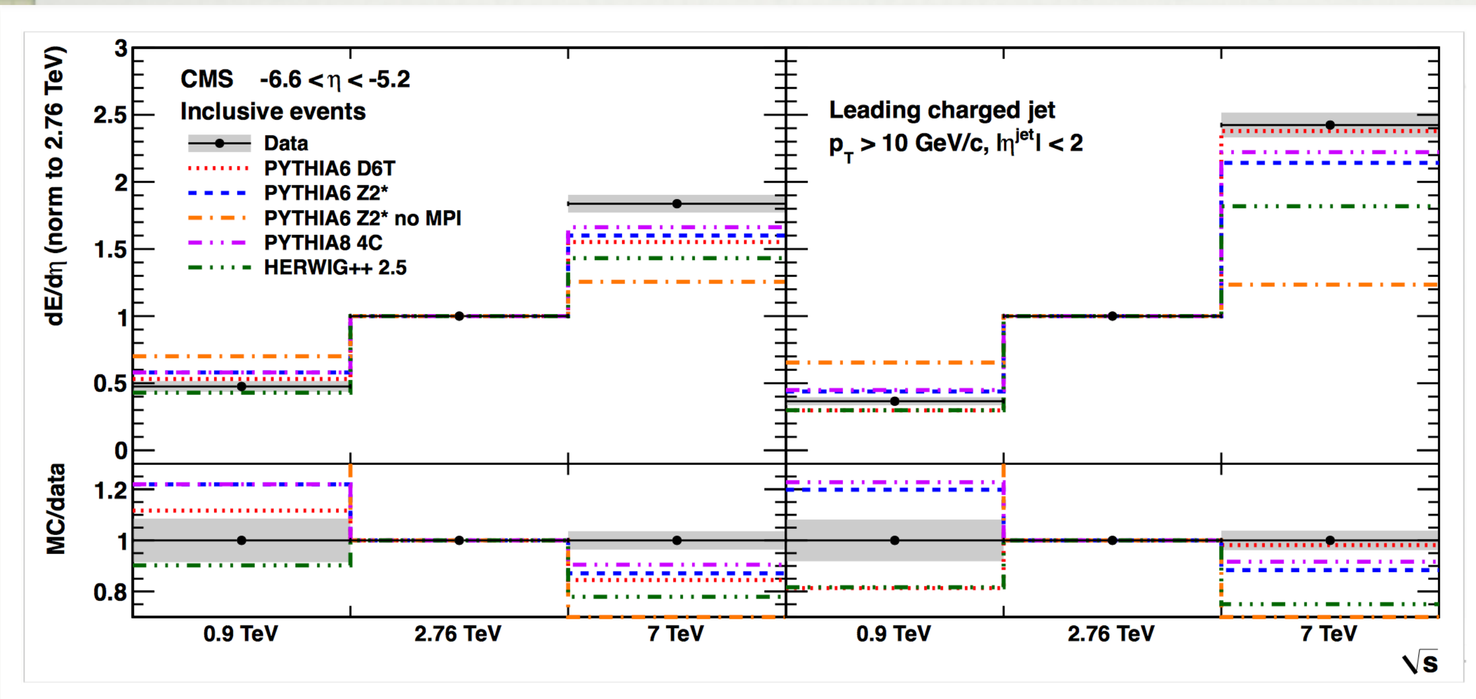
http://arxiv.org/pdf/1110.0211v1.pdf

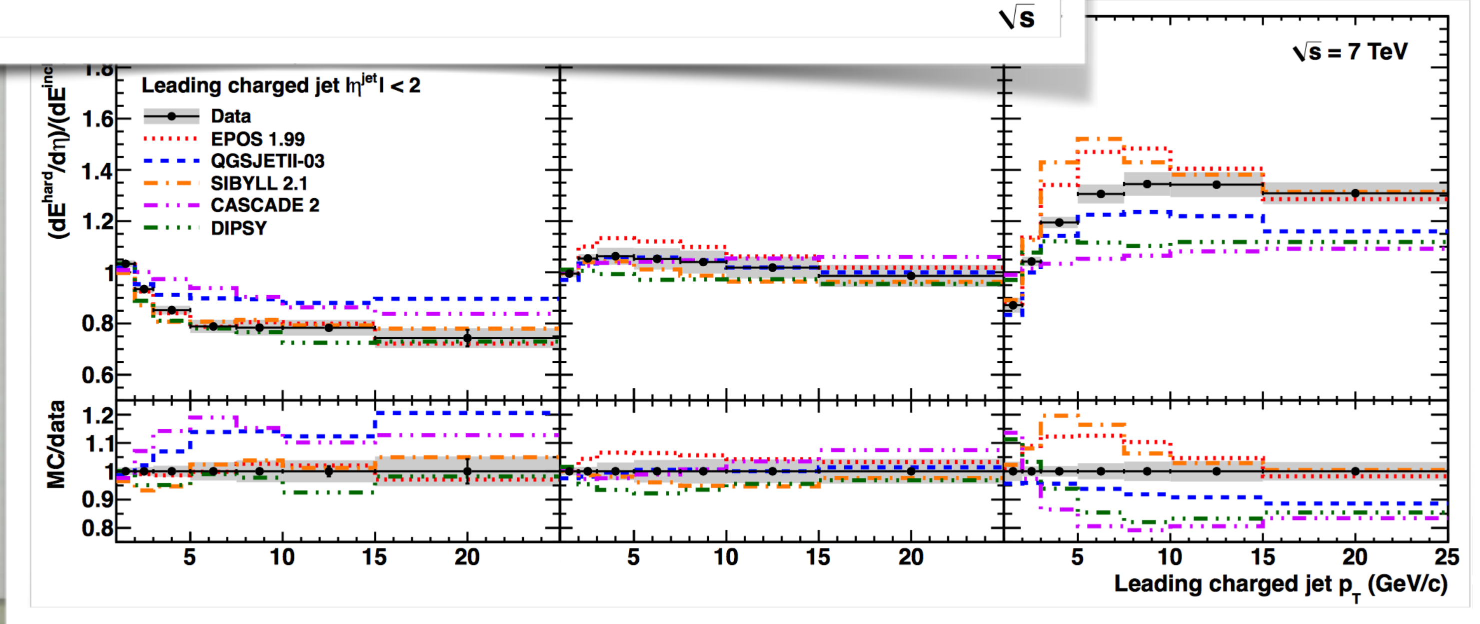




CMS

CASTOR ENERGY FLOW

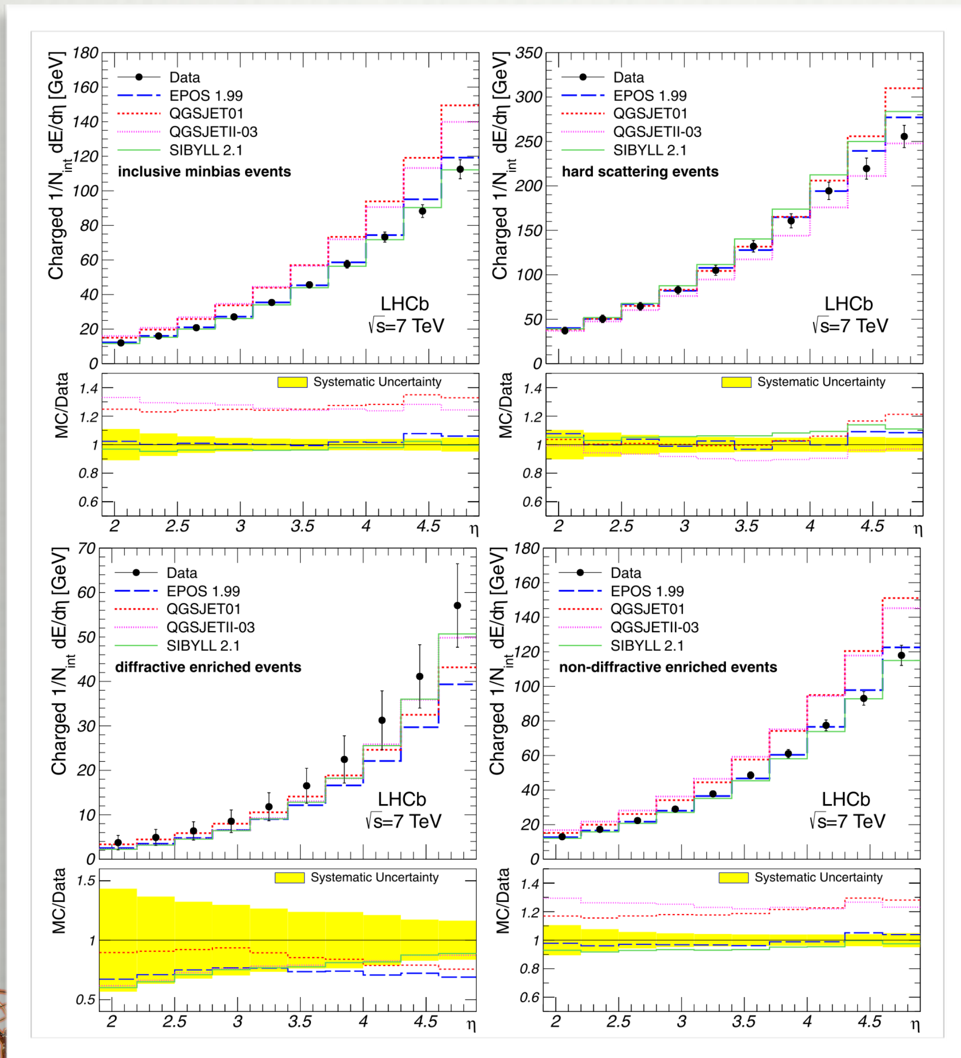


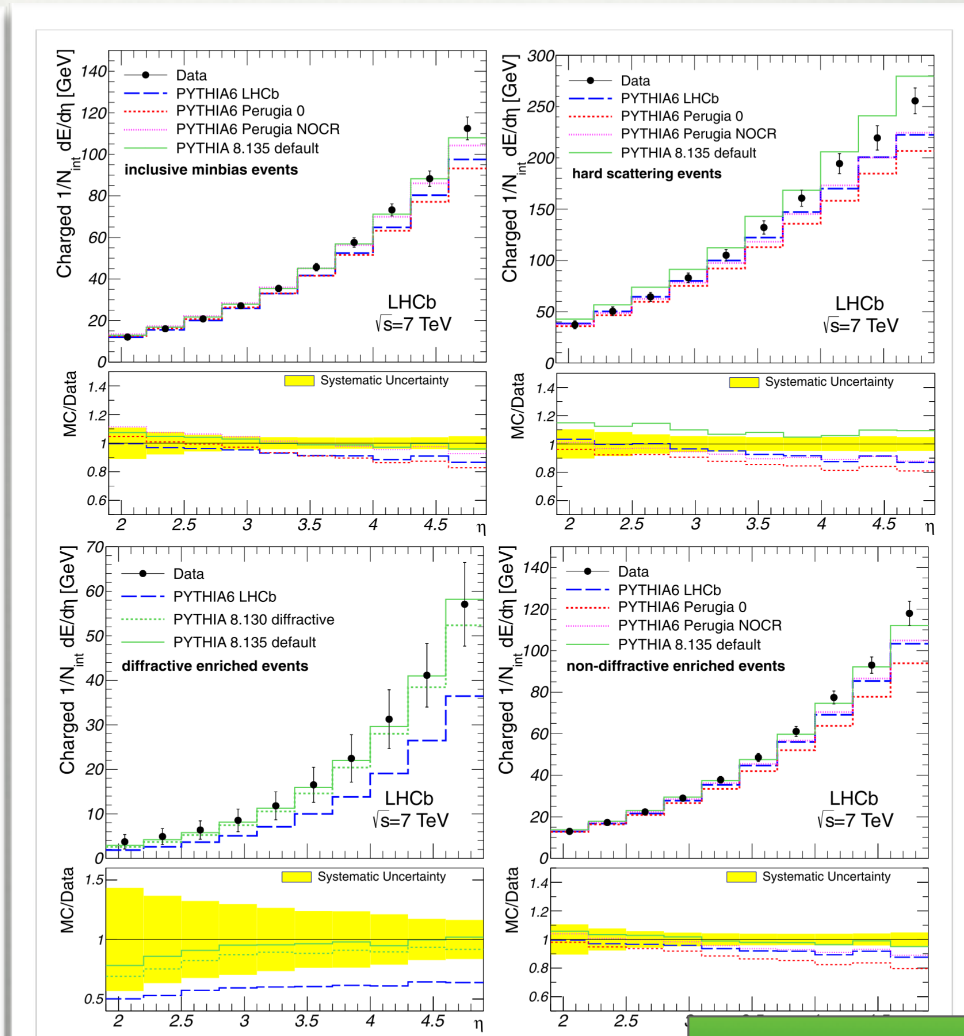


CHARGED ENERGY FLOW

$$EF = \frac{1}{N_{int}}\frac{dE_{tot}}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{int}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

http://arxiv.org/abs/1212.4755

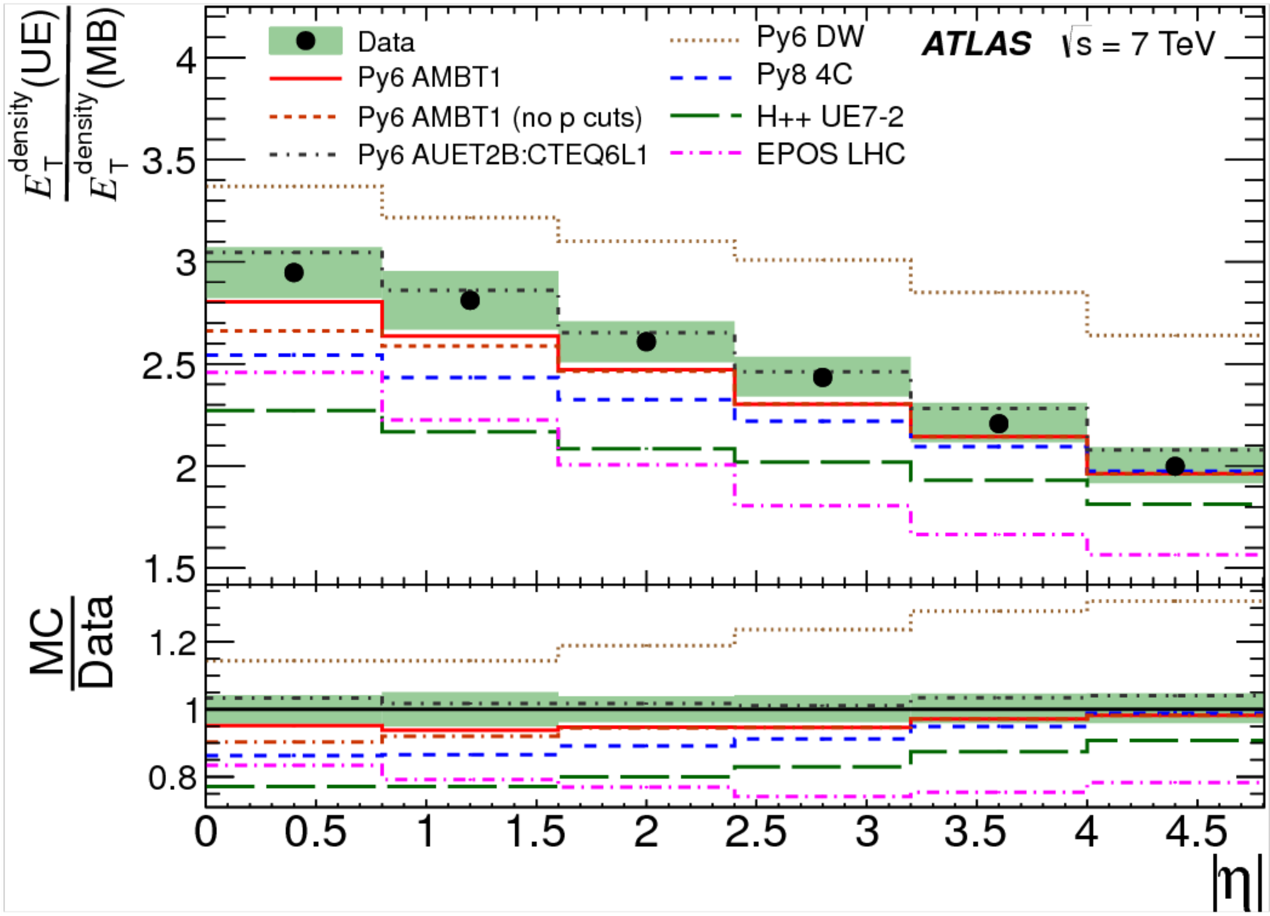




LHCb

CHARGED PARTICLE E_T(UE)/E_T(MB) VS. η

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-44/

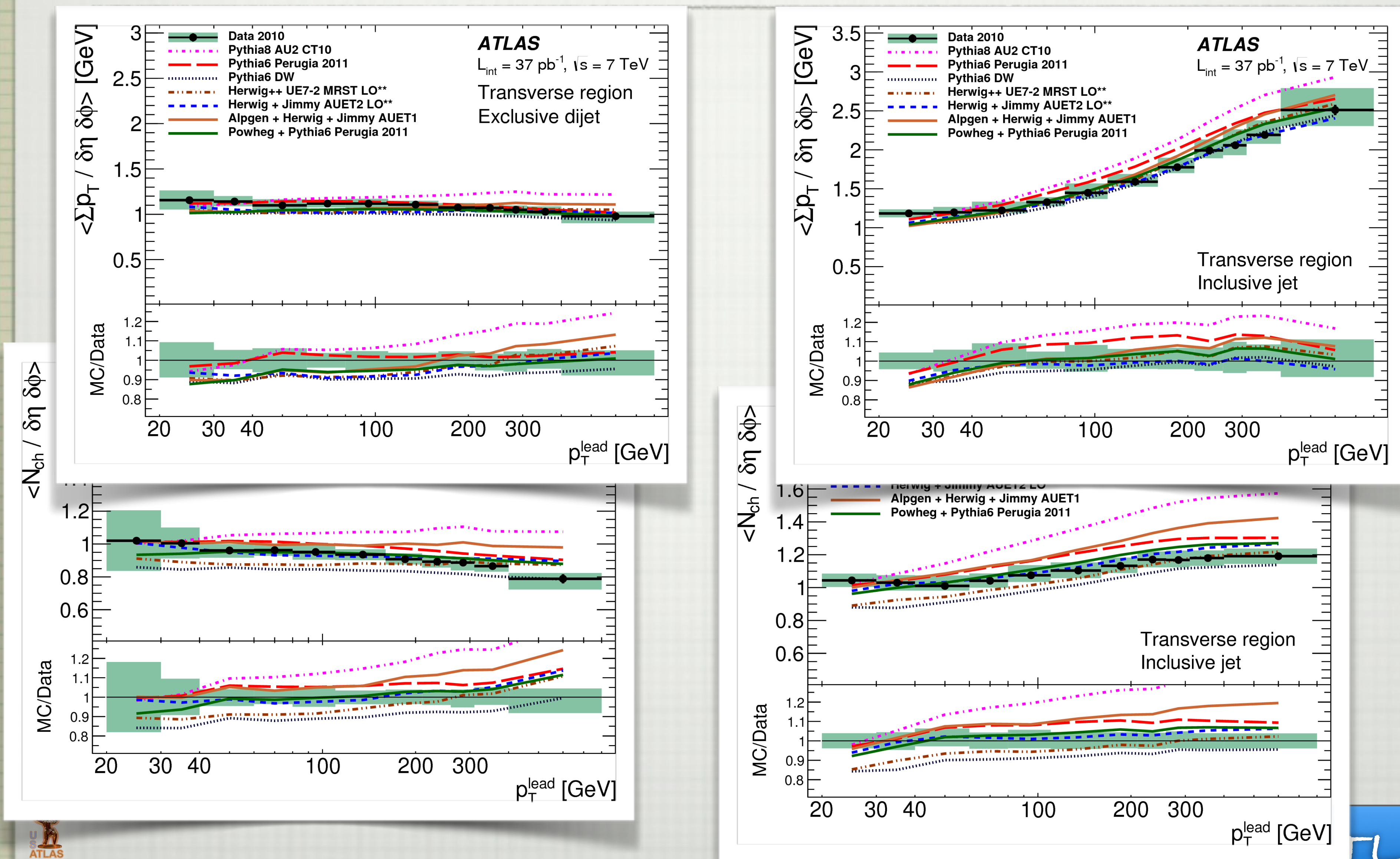


AUET2B (AND AMBT) DESCRIBE

ATLAS

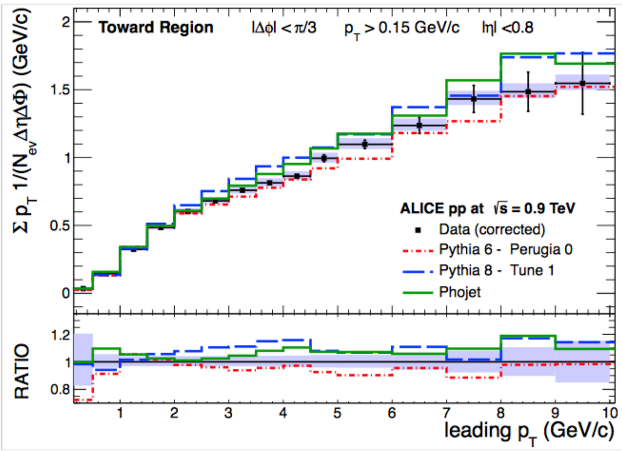
<∑P_T> AND <N_{ch}> VS LEADING JET P_T

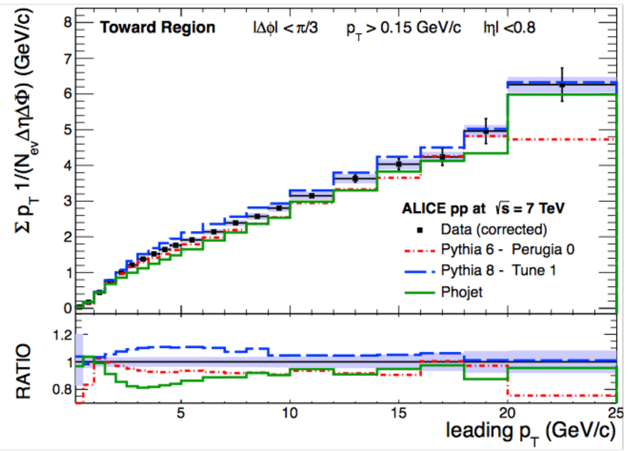
http://arxiv.org/abs/1406.0392

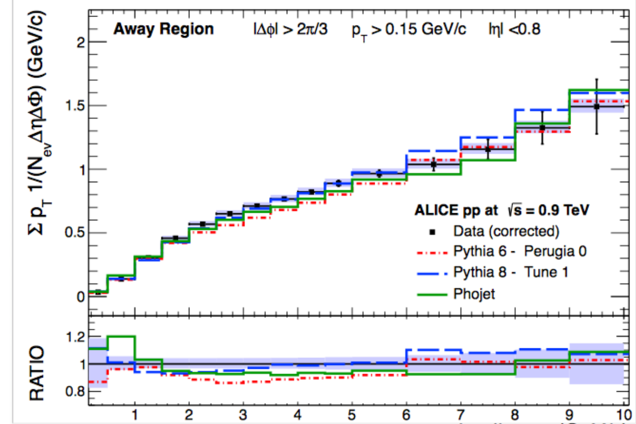


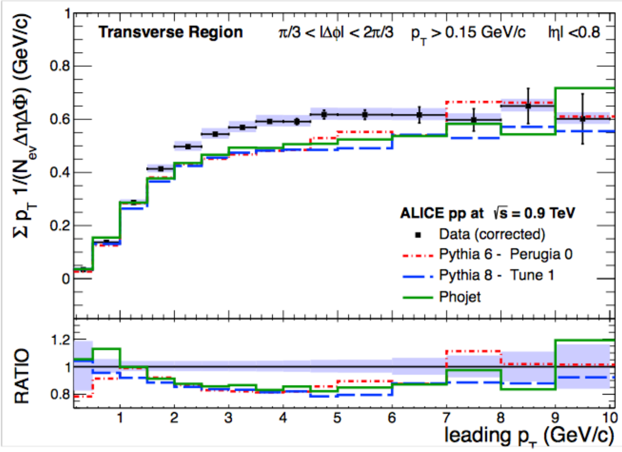
SUMMED P_T VS. LEADING P_T

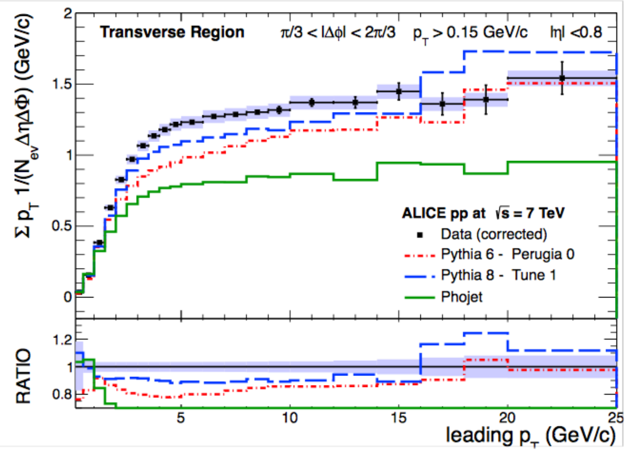
http://link.springer.com/article/10.1007%2FJHEP07%282012%29116

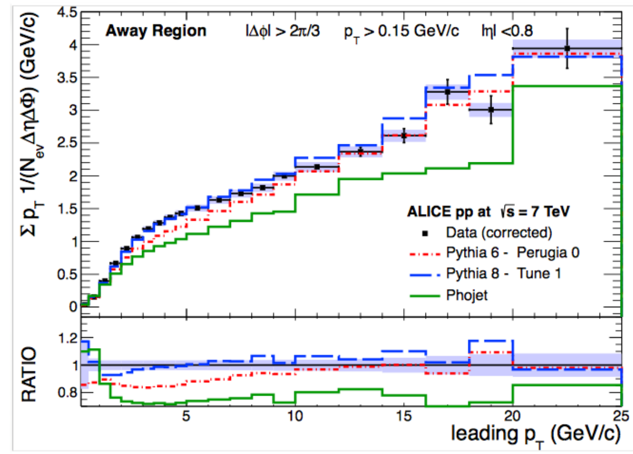








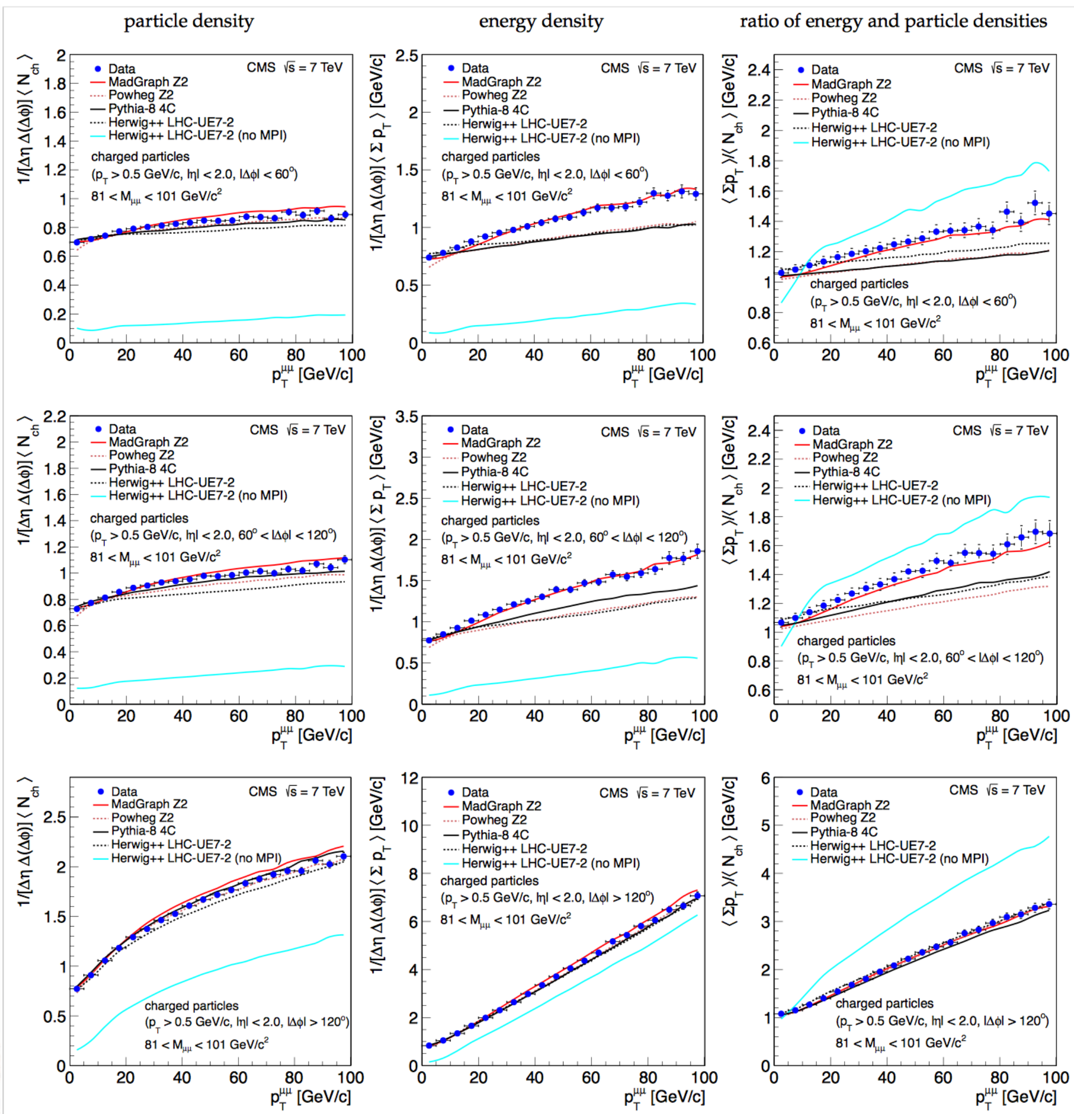




ALICE

DETAILED TRANSVERSE EFFECTS

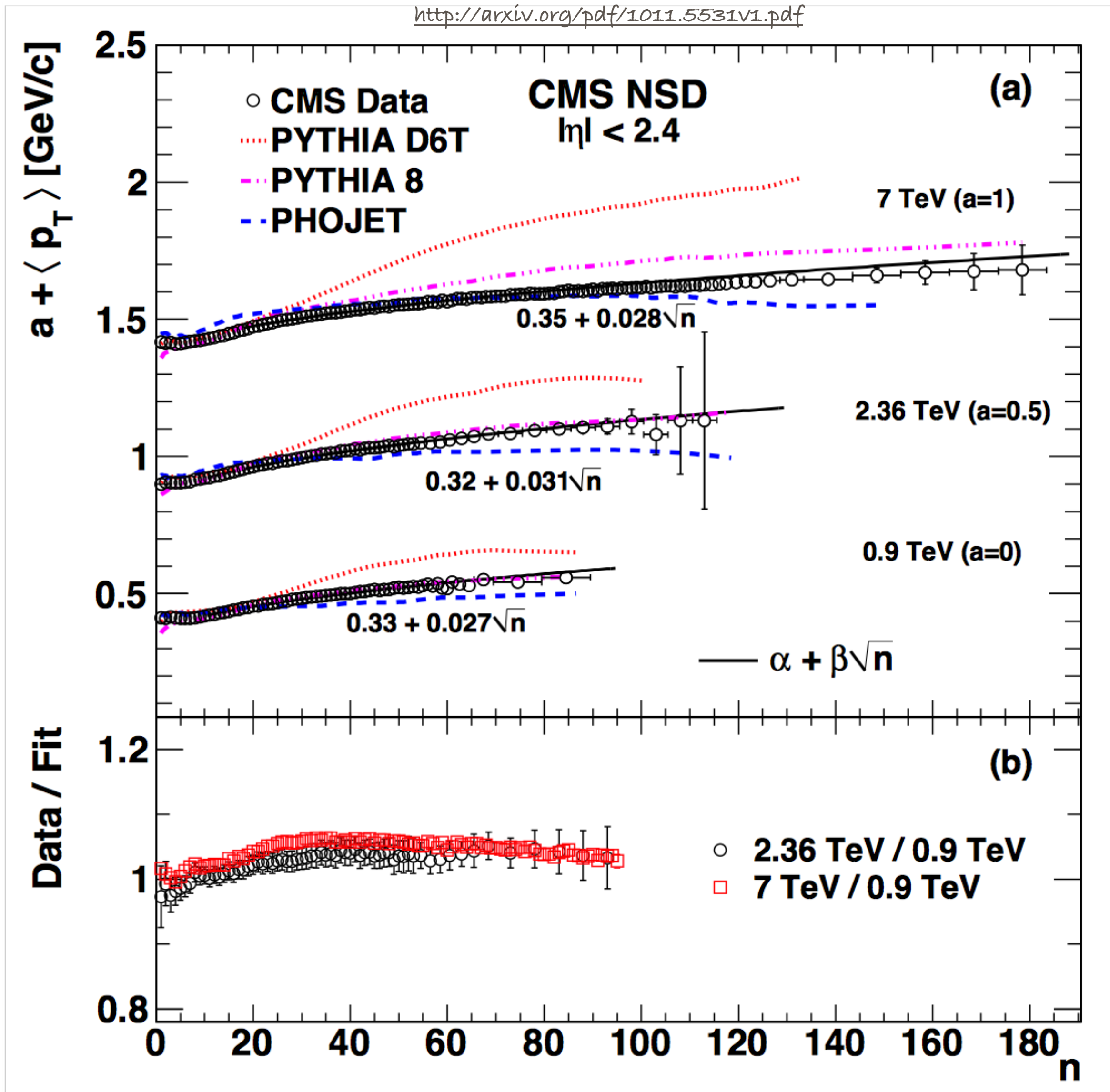
http://arxiv.org/pdf/1204.1411v2.pdf



- ☐ Separated by forward/transverse/backward samples
- ☐ Third column: proportion of sum p_T to charged particle multiplicity wrt the p_T of the dimuon pair

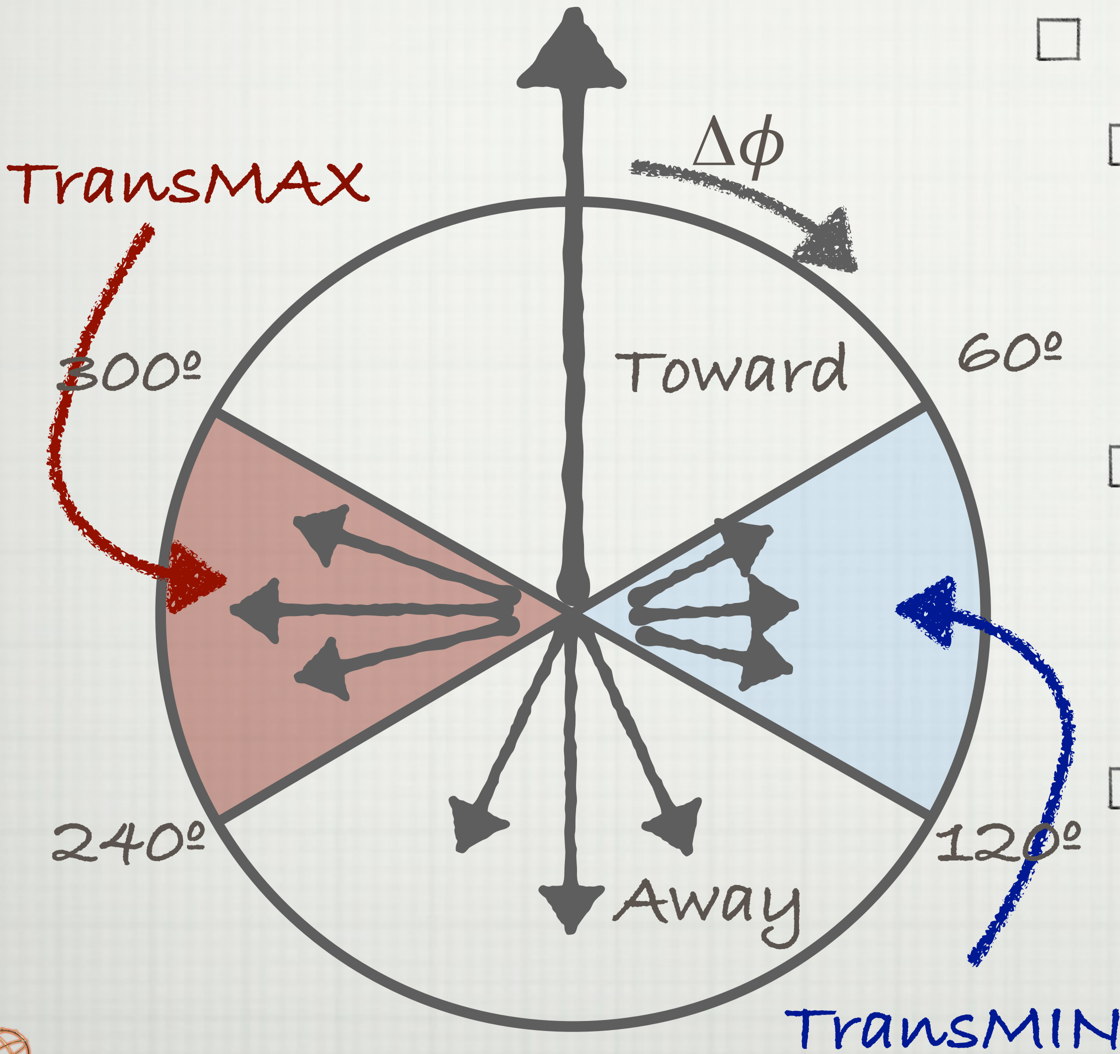
CMS

CMS <P_T> VS. N



CMS

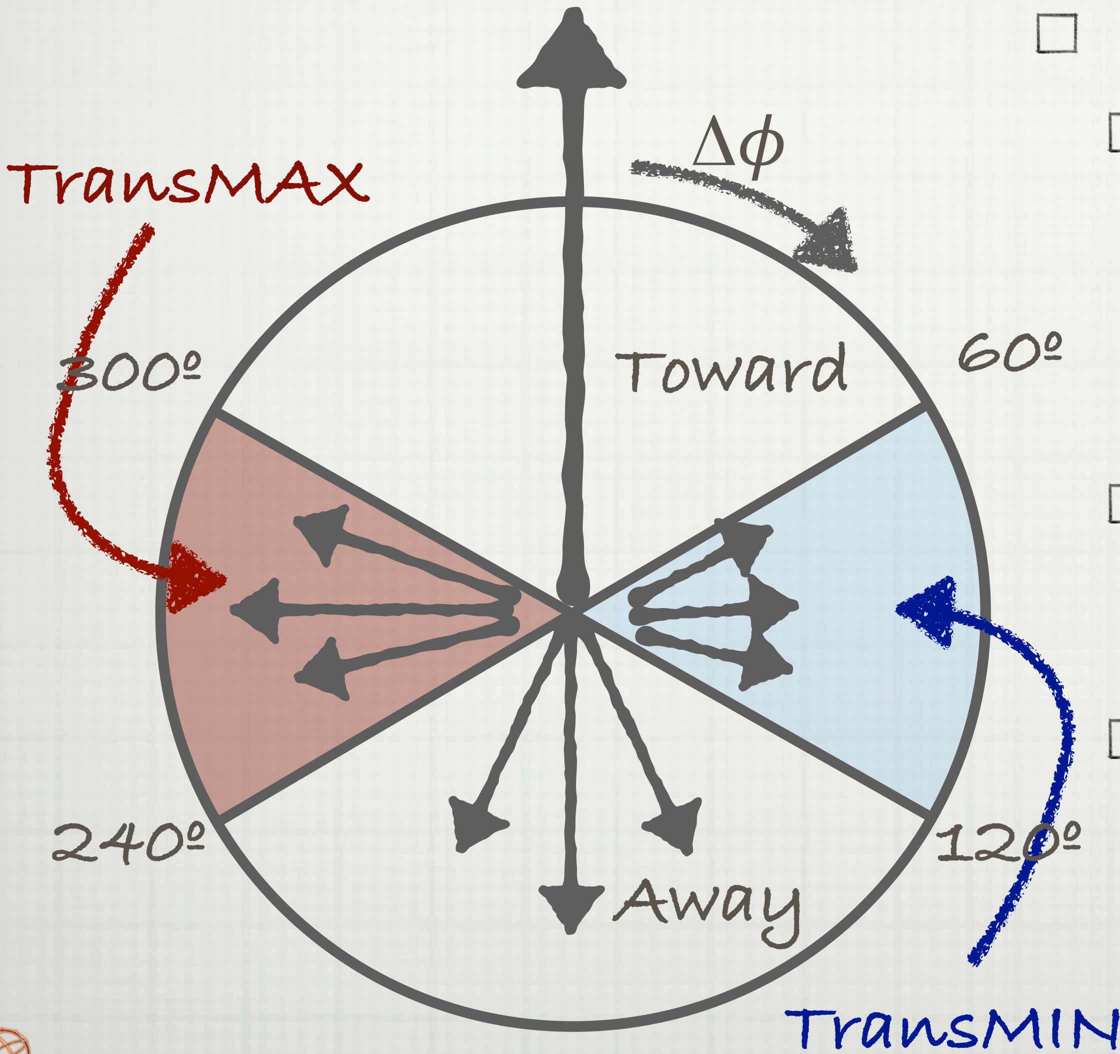
MPI OBSERVABLES BY EXPERIMENT



- CMS
  - Widest forward calorimeter reach via CASTOR, TOTEM T1 and T2, HF/FCal
  - Central tracking and calo improve jet finding for dijet, W and Z techniques
  - Central tracking and calo for high-res charged particle density measurements

CMS

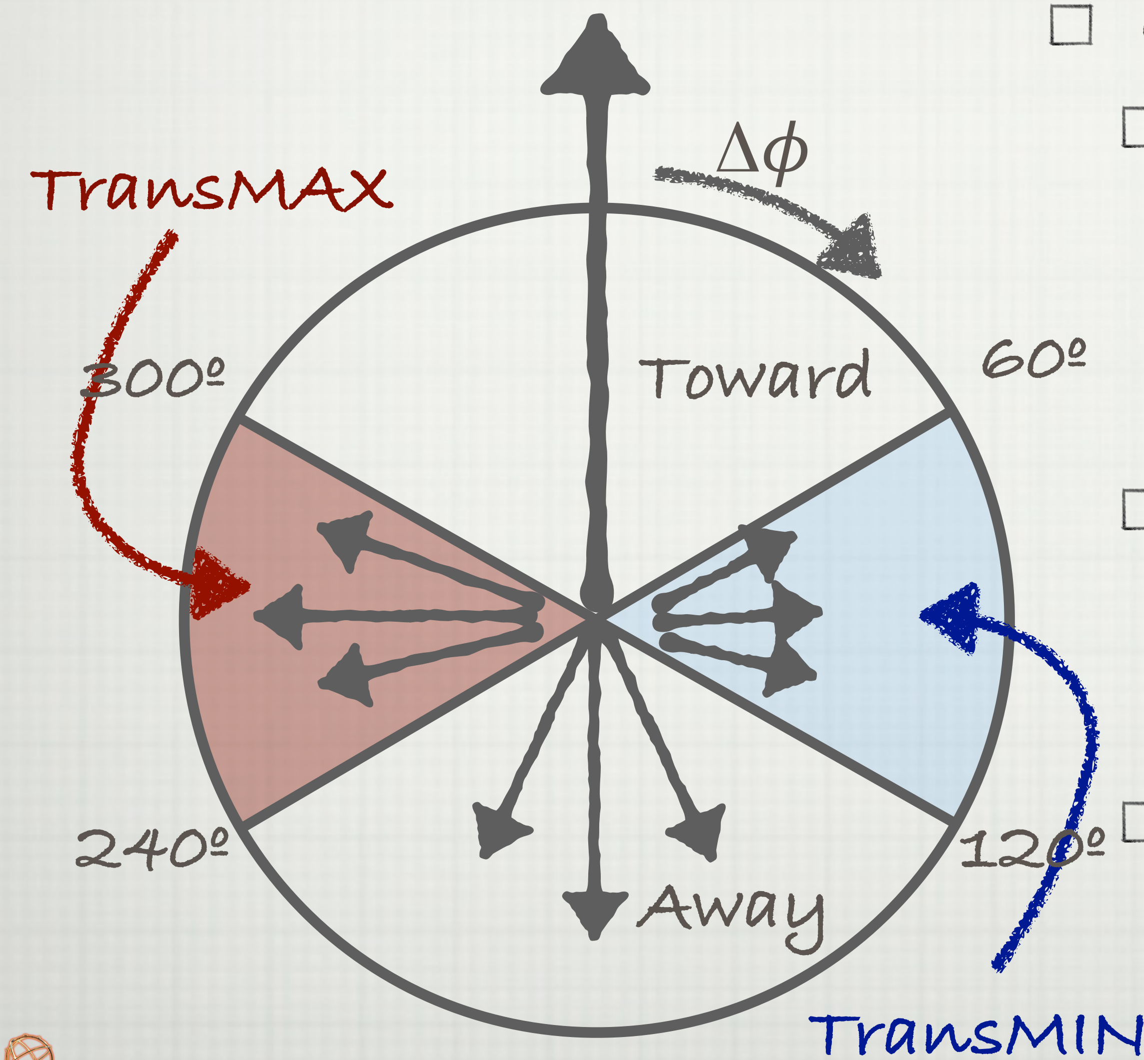
MPI OBSERVABLES BY EXPERIMENT



- ATLAS
  - Central tracking and calo improve jet finding for dijet, W and Z techniques, high-res charged particle density measurements
  - Forward calorimetry for broader energy flow measurements
  - ALFA and AFP allow differentiation between minbias channels by allowing detection of far forward intact protons

ATLAS

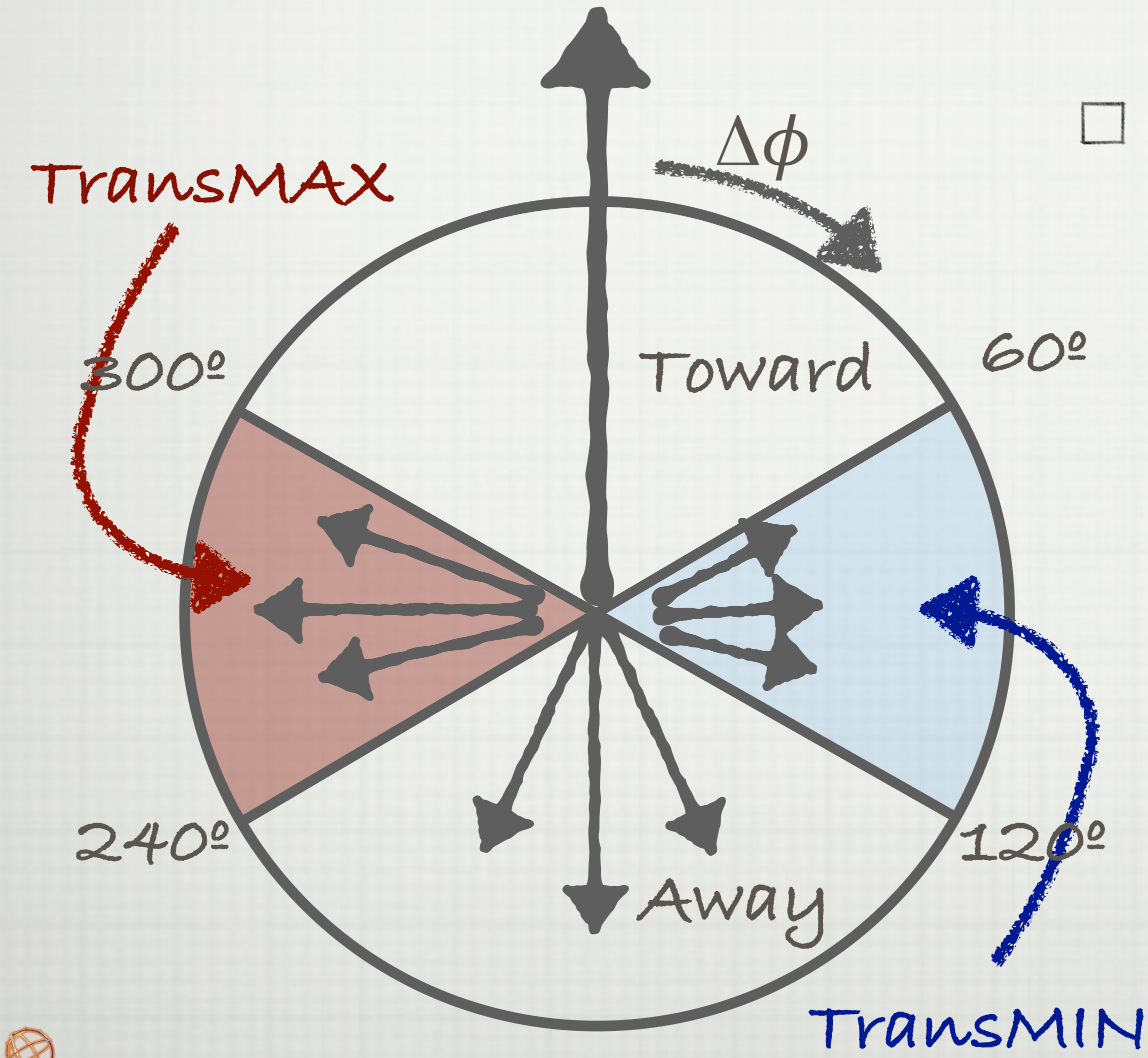
MPI OBSERVABLES BY EXPERIMENT



- LHCb
  - Excellent forward tracking, calo, and particle ID allow for forward charged and neutral energy flow studies.
  - No central detector! Since it's all forward, no way to use dijets specifically, uses "hard scatter" instead.
  - Forward coverage of charged particle density measurements to complement CMS/ATLAS

LHCb

MPI OBSERVABLES BY EXPERIMENT



- ALICE
  - All central – no coverage outside $|\eta| < 1$
  - Finely segmented tracking and strong in particle ID, within its bounds

ALICE

CMS COVERAGE

Figure adapted from R. Orava (2006) and V. Oreshkin (2011)