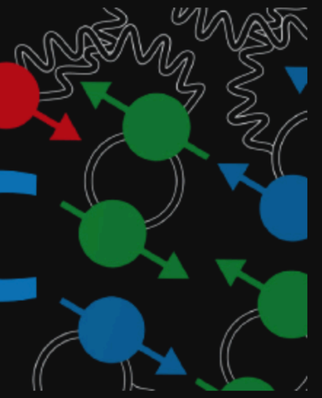

12th International workshop on Multiple Partonic Interactions at the LHC

11-15 October 2021
LIP Lisbon

A PYTHIA 8 Underlying Event Tune for RHIC Energies

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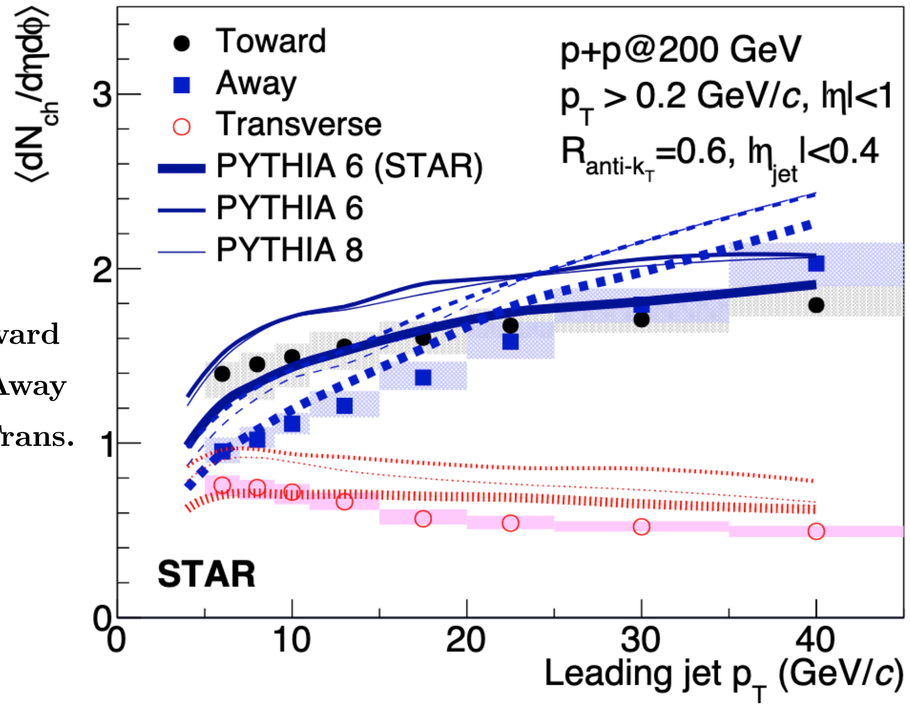
Wayne State University

Supported in part by
U.S. DEPARTMENT OF ENERGY
Office of Science

Introduction

*P. Gunnellini *et al.*
Eur. Phys. J. C (2018) 78: 521

STAR Phys. Rev. D 101, 052004 (2020)



Solid Lines = Toward
Dashed Lines = Away
Dotted Lines = Trans.

$$p_{T,0} = p_{T,0}^{Ref}\left(\frac{\sqrt{s}}{\sqrt{s_{Ref}}}\right)^{ecmPow}$$

PYTHIA 6 "STAR" tune adjusted power law extrapolation parameter (PARP(90)=0.24→ 0.213) to match low-p_T $\pi^{\pm}$ yields
STAR Phys. Rev. D100, 052005 (2019)

Modeling of Multi-Parton Interactions (MPI) in PYTHIA essential to simulate underlying event (UE) in hadron collisions

- Key component: Regularization parameter $p_{T,0}$

Collision energy extrapolation of $p_{T,0}$ follows power law function

- Reference energy usually 7 TeV; accurate extrapolation down to 200 GeV is not easy (see also*)

Tuning Strategy

Parametrization-based tuning methodology: *Professor* toolkit
(professor.hepforge.org)

- Polynomial parameterization of generated Monte Carlo (MC) data w/ parameter variation
- χ^2 min. w.r.t. data

$p \equiv$ tunable parameter space

$$\mathrm{MC}_b(\boldsymbol{p}) \approx f^{(b)}(\boldsymbol{p}) = \alpha_0^{(b)} + \sum_i \beta_i^{(b)}\, p'_i + \sum_{i \le j} \gamma_{ij}^{(b)}\, p'_i\, p'_j$$

MC response in one data bin b

$$\chi^2(\boldsymbol{p}) = \sum_{\mathcal{O}} w_{\mathcal{O}} \sum_{b \in \mathcal{O}} \frac{(f^{(b)}(\boldsymbol{p}) - \mathcal{R}_b)^2}{\Delta_b^2}$$

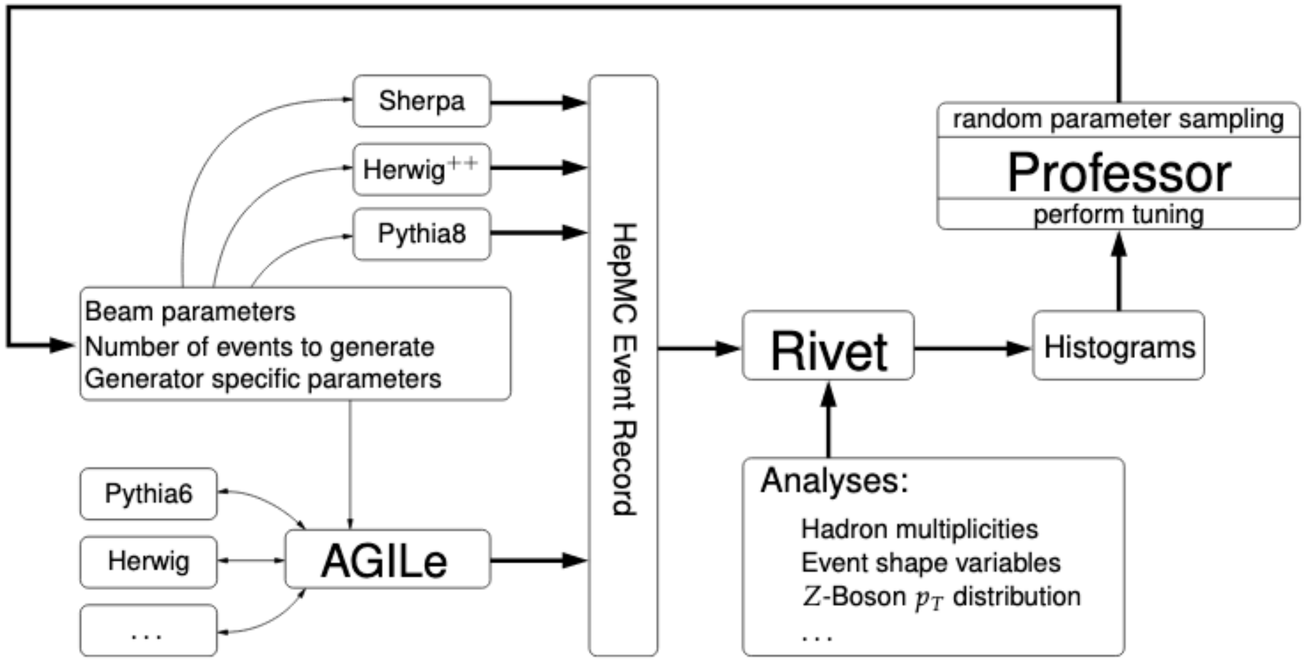


Image credit: Holger Schulz's Thesis
professor.hepforge.org/diplomathesis_h_schulz.pdf

Professor+PYTHIA6 Tune: https://doi.org/10.1140/epjc/s10052-009-1196-7
CMS PYTHIA6,8 Herwig++ Tune: https://doi.org/10.1140/epjc/s10052-016-3988-x
CMS Herwig 7 Tune: arXiv:2011.03422
....

Tuning Parameters and Observables

Starting point is PYTHIA 8.303 with prepackaged Monash* tune

NNPDF 2.3→NNPDF 3.1

- Leading order, $\alpha_s(m_Z) = 0.130$

Reference energy switched to 200 GeV

TABLE I. PYTHIA 8 settings and tuning parameters.

Setting	Default	New
PDF:pSet	13	17
MultipartonInteractions:ecmRef	7 TeV	200 GeV
MultipartonInteractions:bprofile	3	2
Tuning Parameter	**Default**	**Range**
MultipartonInteractions:pT0Ref	2.28 GeV	0.5-2.5 GeV
MultipartonInteractions:ecmPow	0.215	0.0-0.25
MultipartonInteractions:coreRadius	0.4	0.1-1.0
MultipartonInteractions:coreFraction	0.5	0.0-1.0
ColourReconnection:range	1.8	1.0-9.0

TABLE II. Mid-rapidity data used in the tuning procedure.

Experiment	$\sqrt{s}$ (GeV)	Observable	Reference
STAR	200	$\pi^{\pm}$ cross sections vs. p_T	Physics Letters B 637, 161 (2006)
PHENIX	200	Di-muon pairs from Drell-Yan vs. di-muon p_T	Phys. Rev. D 99, 072003 (2019)
STAR	200	Average charged particle multiplicities and p_T vs. leading jet p_T in the forward, transverse, and away regions	Phys. Rev. D 101, 052004 (2020)
CDF	300, 900, 1960	Charge particle density and $\sum p_T$ vs. leading hadron p_T in transverse region	Phys. Rev. D 92, 092009 (2015)
STAR	200	SoftDrop groomed jet sub-structure (z_g and R_g)	Physics Letters B 811, 135846 (2020)
STAR	200	Inclusive and groomed jet mass	Phys. Rev. D 104, 052007 (2021)

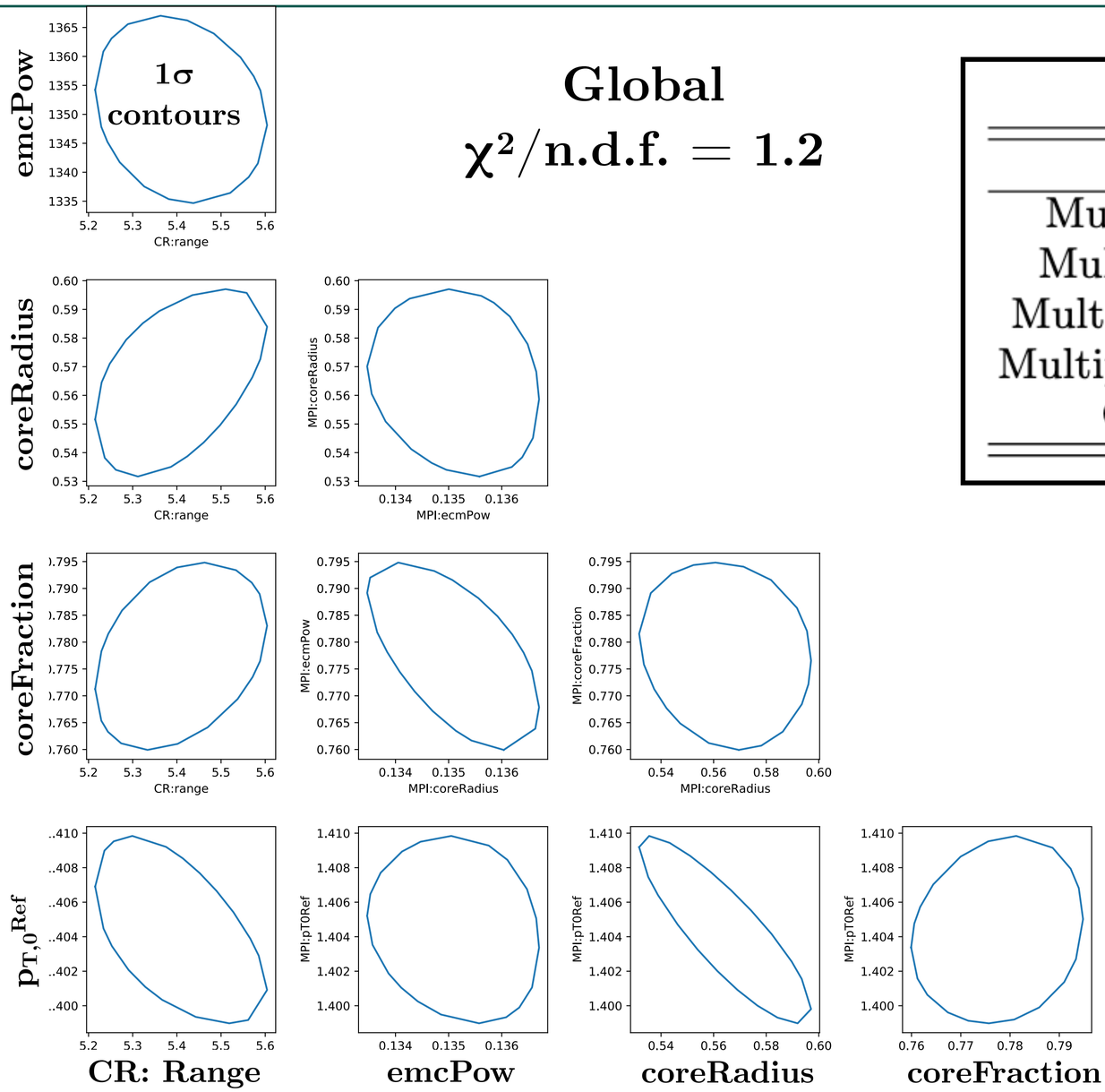
New From STAR

Included in RIVET

Degrees of Freedom= 493

*P. Skands *et al.* Eur. Phys. J. C74, 3024 (2014)

Tune Results: The 'Detroit' Tune

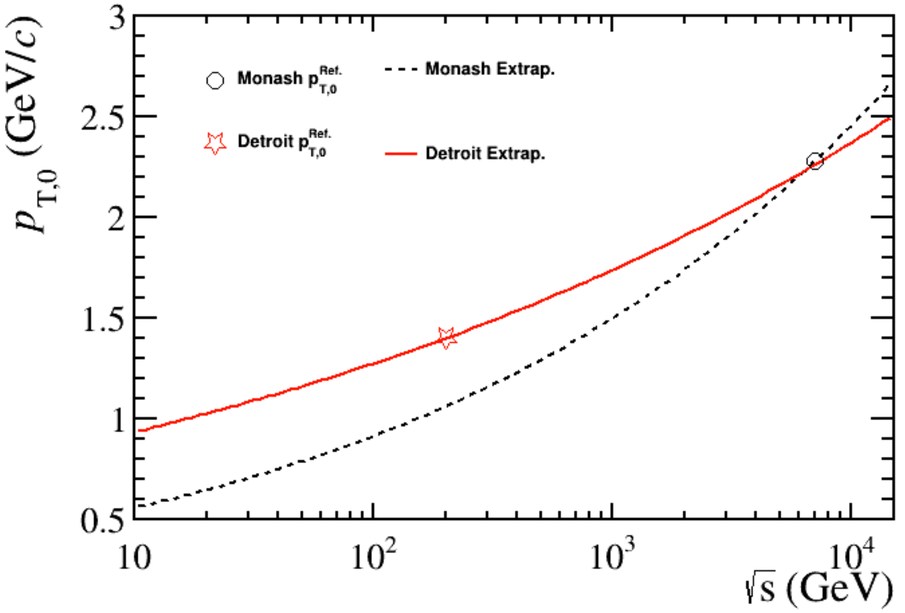


Global

$\chi^2/\text{n.d.f.} = 1.2$

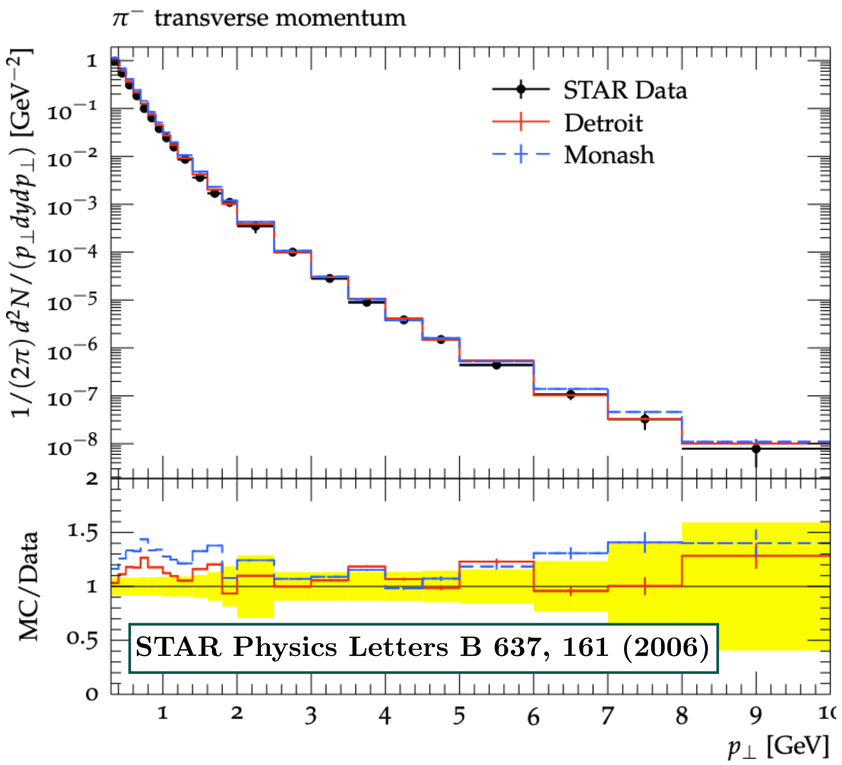
TABLE III. PYTHIA 8 tuned parameters.

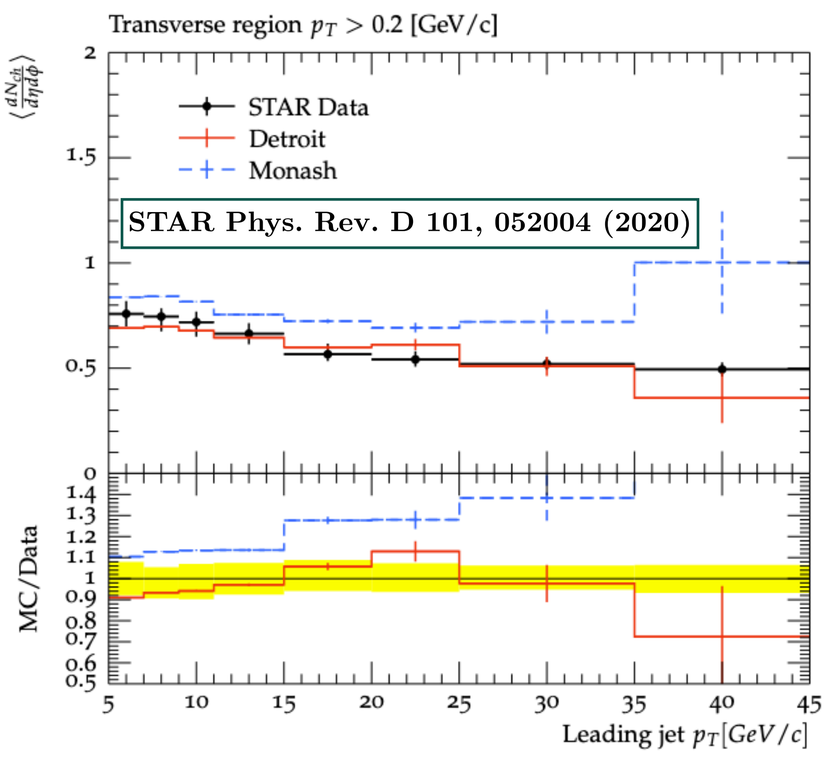
Tuning Parameter	Default	New
MultipartonInteractions:pT0Ref	2.28 GeV	1.40 GeV
MultipartonInteractions:ecmPow	0.215	0.135
MultipartonInteractions:coreRadius	0.4	0.56
MultipartonInteractions:coreFraction	0.5	0.78
ColourReconnection:range	1.8	5.4

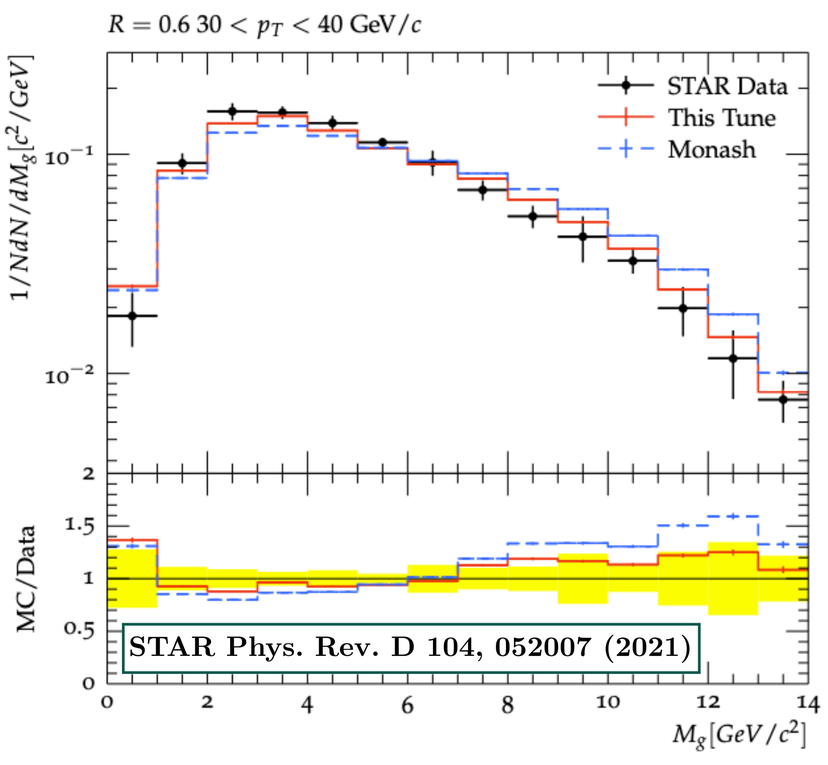


New PYTHIA 8 Performance

Representative plots (see backup)







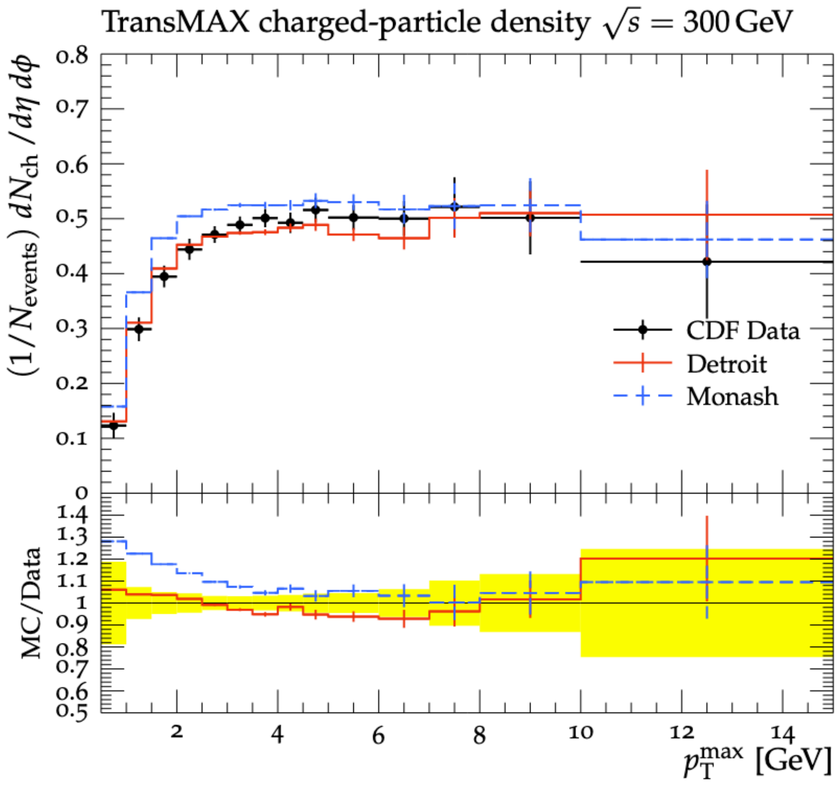
Significant improvement of pion spectrum and underlying event description @ 200 GeV

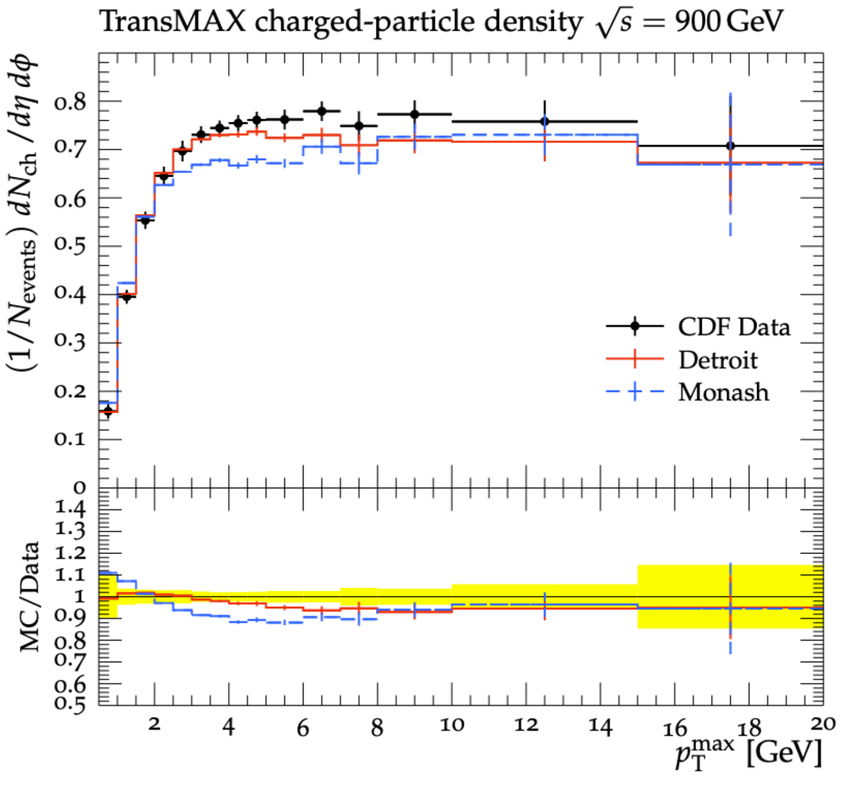
Additional improvements in jet sub-structure and Drell-Yan (backup)

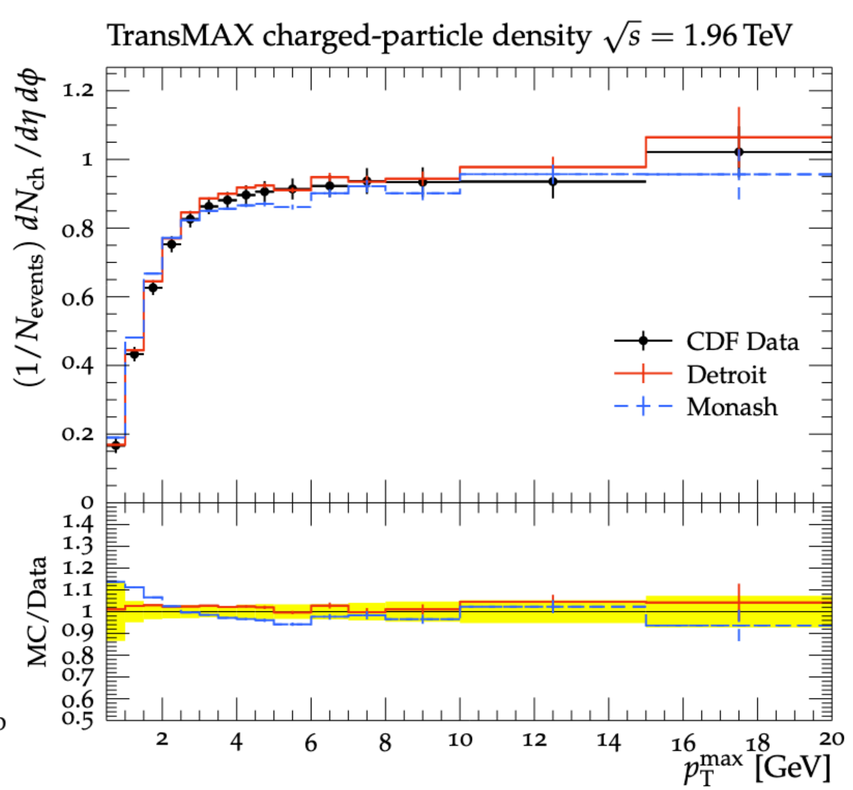
Yellow bands show data uncertainties only

Energy Dependence: 300-1960 GeV

CDF Phys. Rev. D 92, 092009 (2015)



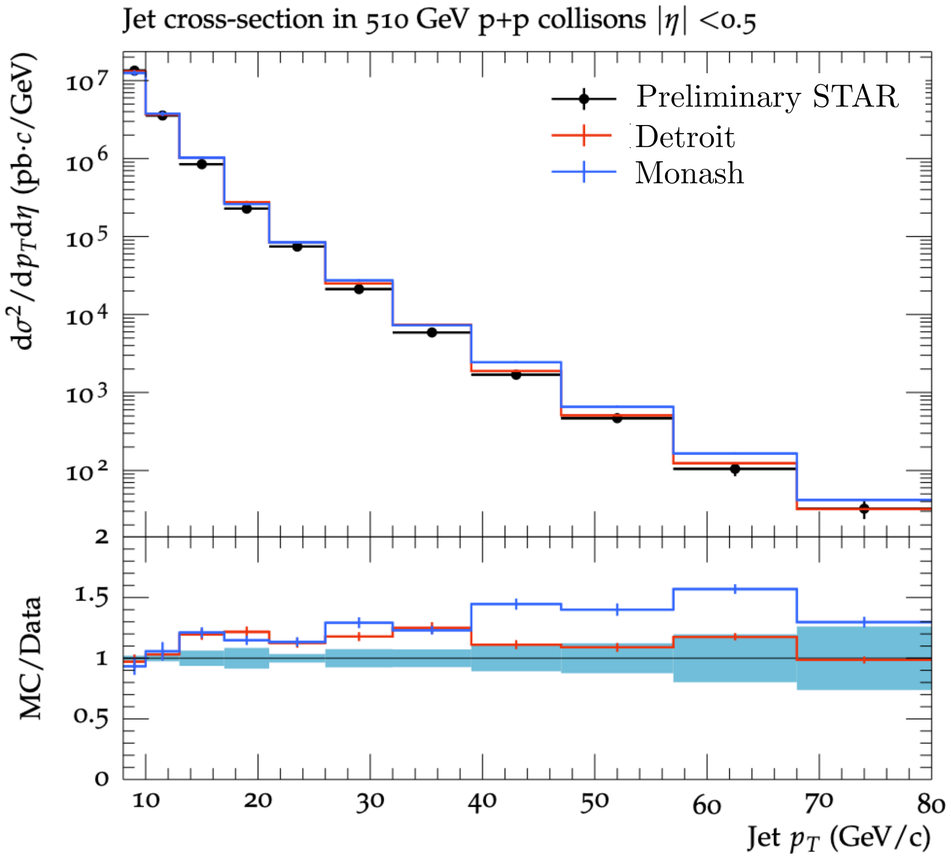


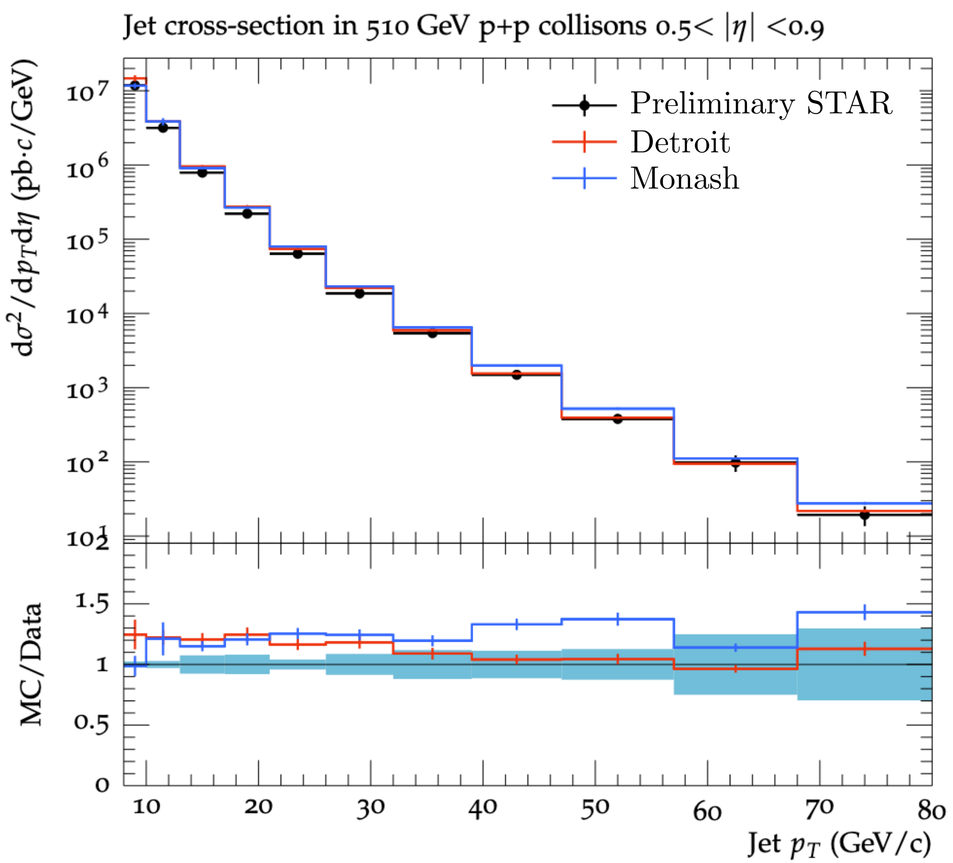


Representative plots at each energy; similar comparisons for p_T sum and transMIN

Good agreement with data valid across all center-of-mass energies up to 1.96 TeV

Energy Dependence: $\sqrt{s} = 510$ GeV

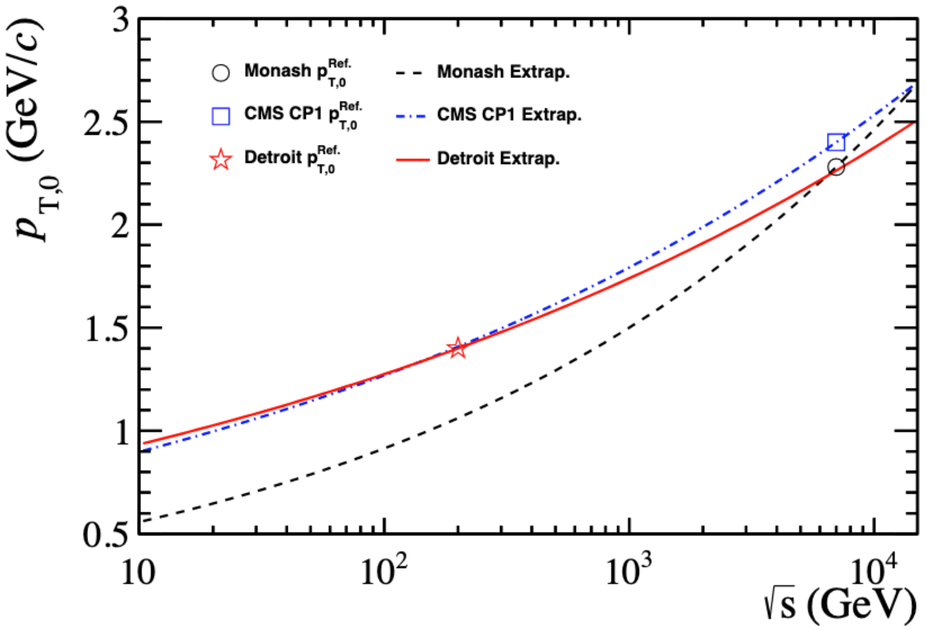


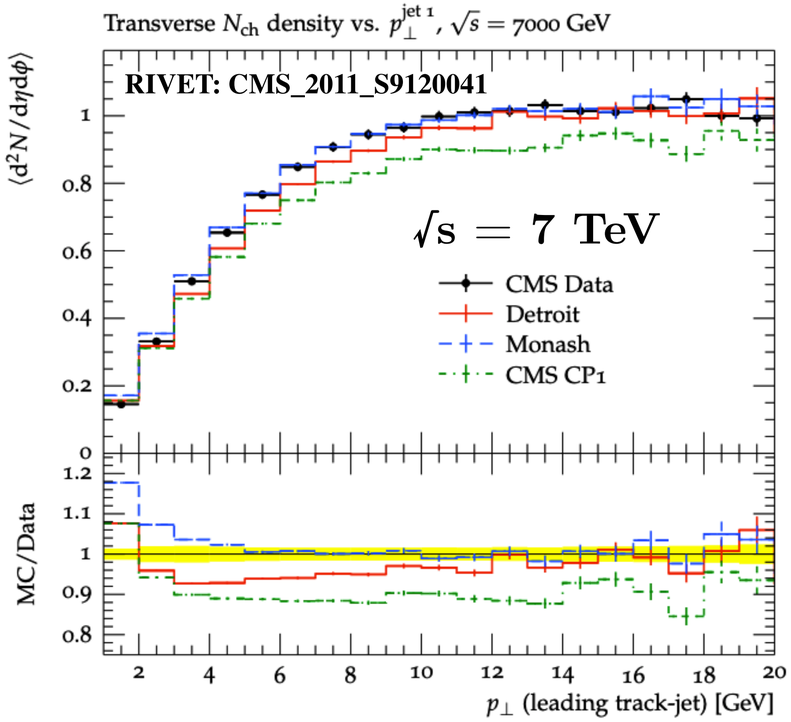


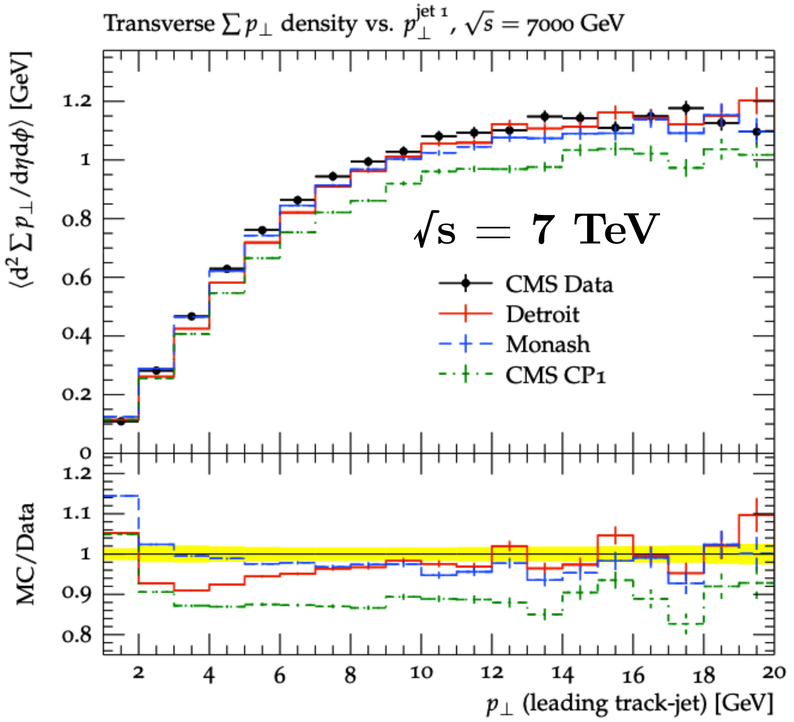
Comparisons with preliminary STAR inclusive jet spectra at 510 GeV improved in shape and scale - largely driven by new proton PDFs

Comparisons at LHC Energies: 7 TeV

CMS Journal of High Energy Physics 2011, 109 (2011)







CMS CP tunes follow similar strategy as this exercise (European Physical Journal C 80, 4 (2020))

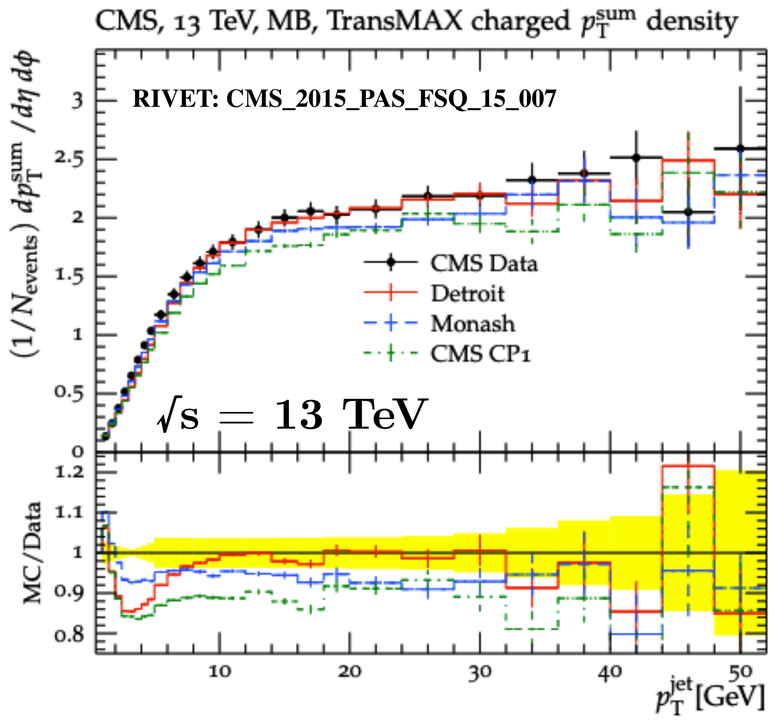
Extrapolation curve for Detroit tune less steep than Monash and CMS CP1 tunes

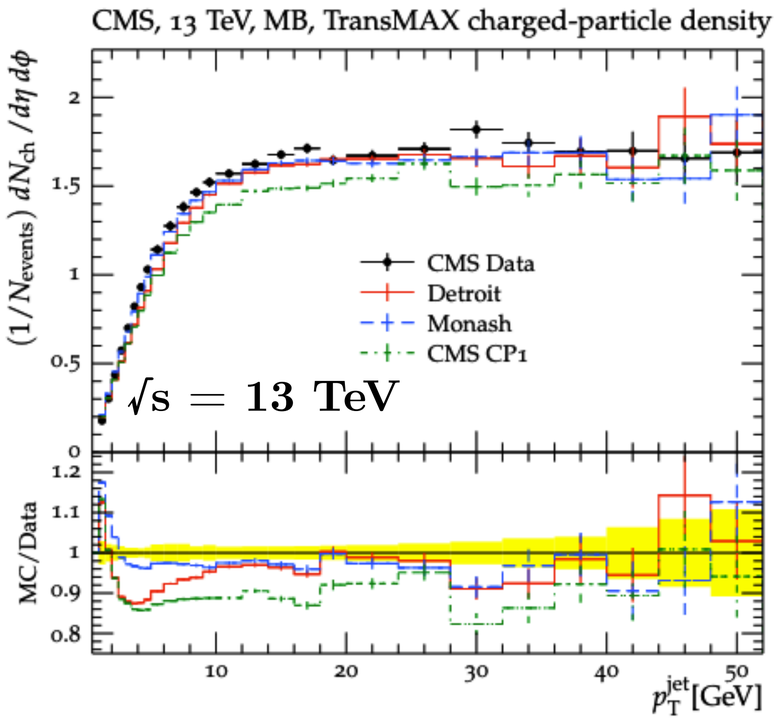
High leading track-jet p_T: Comparable to CMS underlying event data at 7 TeV, and Monash tune; deviations at low p_T

Comparisons at LHC Energies: 13 TeV

CMS 13 TeV: CDS CMS-PAS-FSQ-15-007

Representative plots (see backup)





Comparable or better than Monash tune at high p_T; deviations with data at low p_T

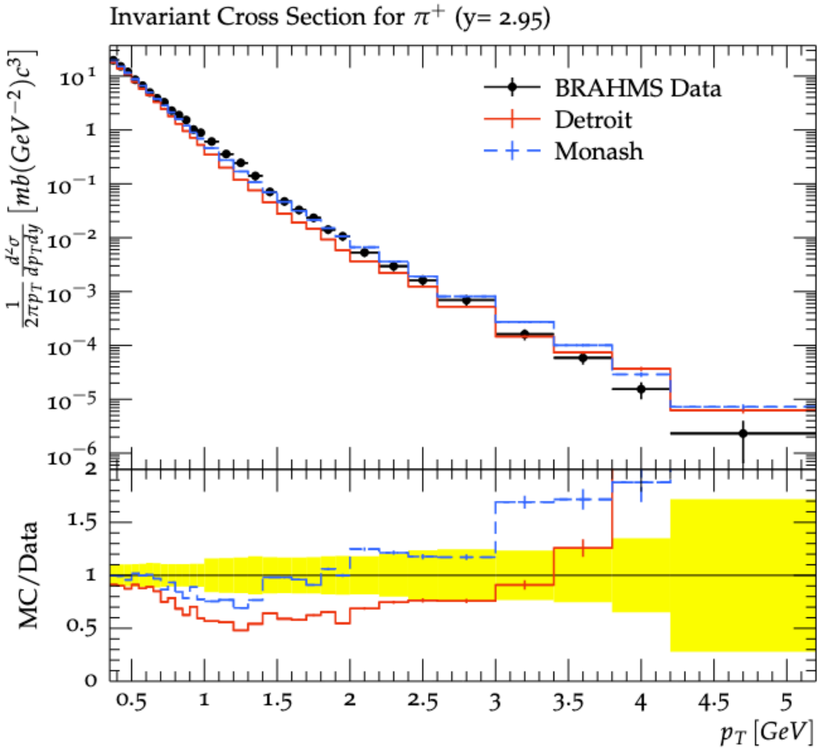
- Likely driven by different proton shape function used

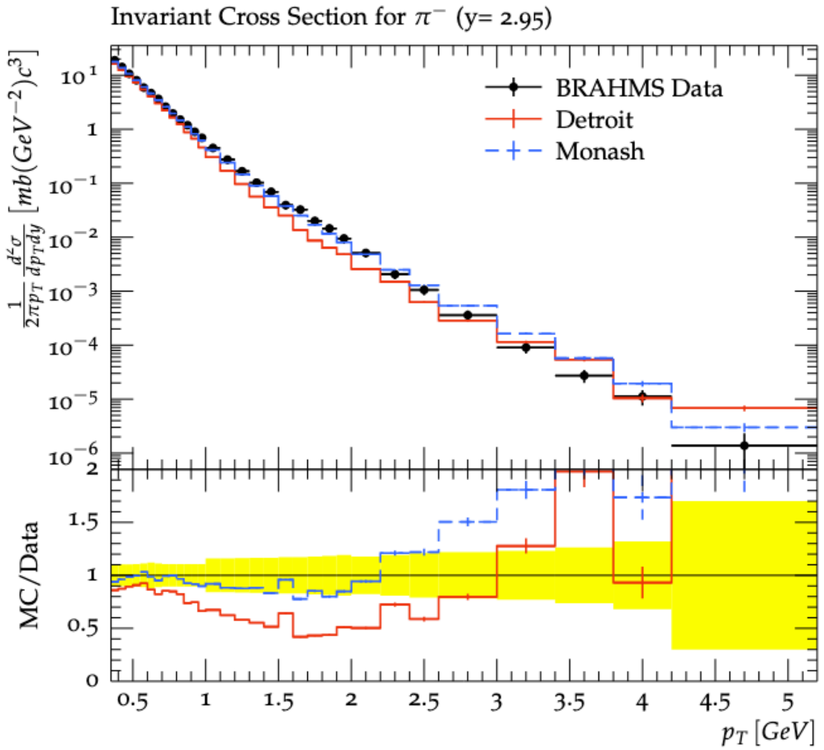
High p_T region significantly impacted by long-lived decays in MC

- Explicitly turned off here; could resolve CMS CP1 discrepancy

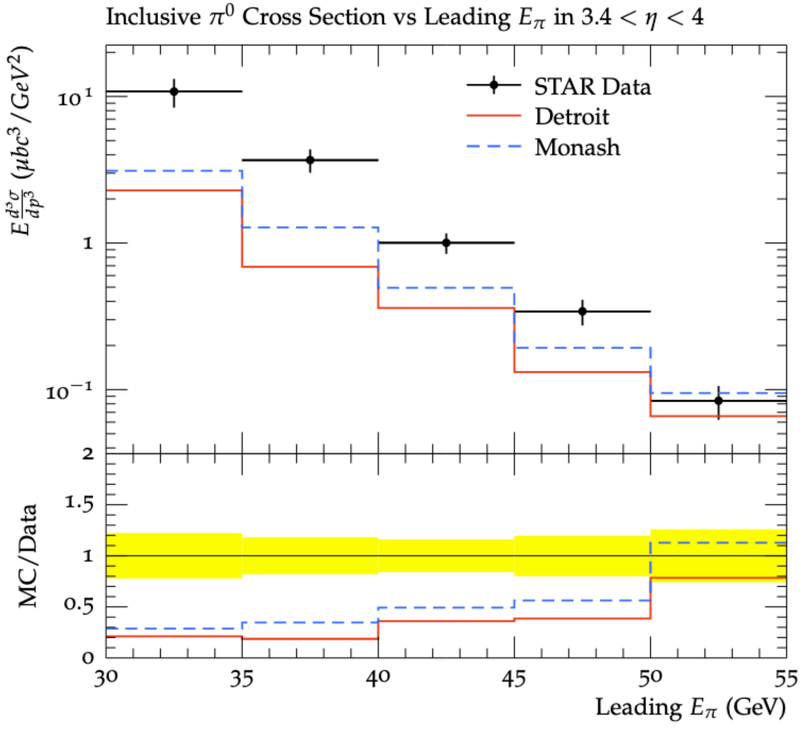
Forward Rapidity Comparisons

BRAHMS Phys. Rev. Lett. 98, 252001 (2007)





Phys. Rev. Lett. 92, 171801 (2004)



Both Monash and Detroit tunes can't describe forward pion spectra from BRAHMS or STAR

- New tune does worse than Monash...
- Simultaneous tune with mid-rapidity and larger tune-able phase space (ISR) unable to recover MC/data agreement

Desirable to resolve for RHIC programs starting in 2022 (forward STAR upgrade), and future Electron-Ion Collider program

Summary

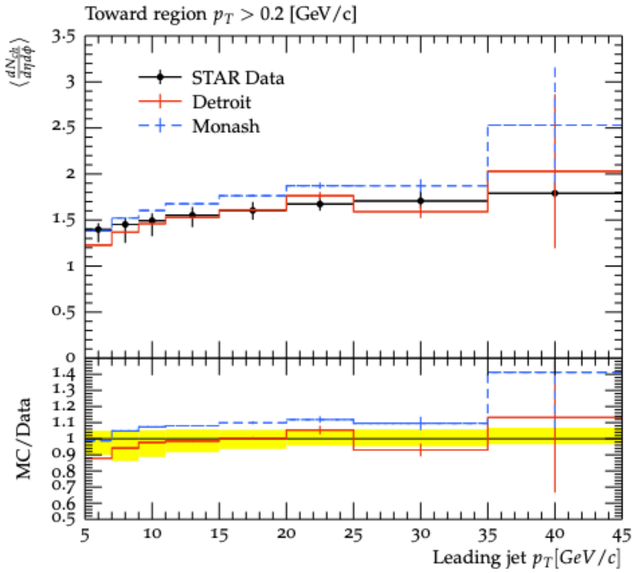
PYTHIA 8 tuned to underlying event data at $\sqrt{s}$ = 200-1960 GeV:
The 'Detroit' Tune

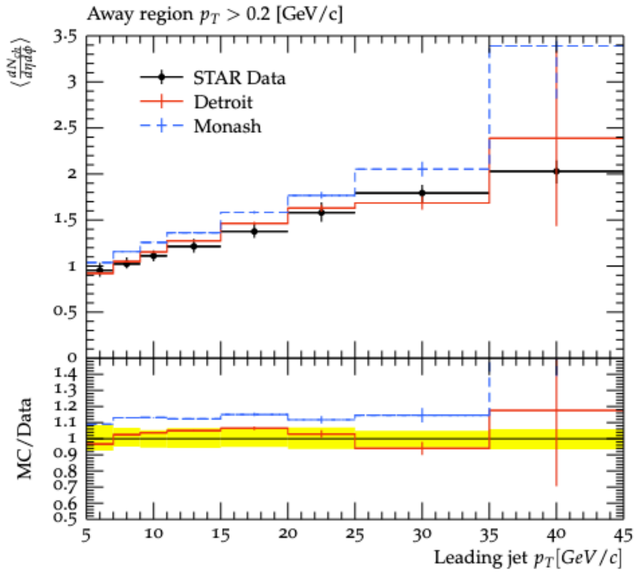
- Significant improvement in the description of data at all energies used in tuning
- Underlying event observables vs. leading particle/jet at high p_T described at $\sqrt{s}$ = 7 and 13 TeV; Comparable or better than Monash tune
- Manuscript in preparation... stay *tuned!*

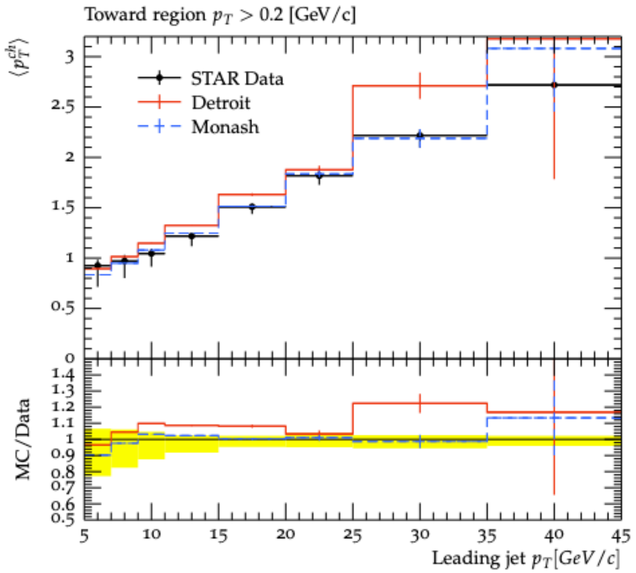
Simultaneous description of both mid- and forward-rapidity data currently not achievable→ Highly desired for upcoming (2022+) STAR forward upgrade data!

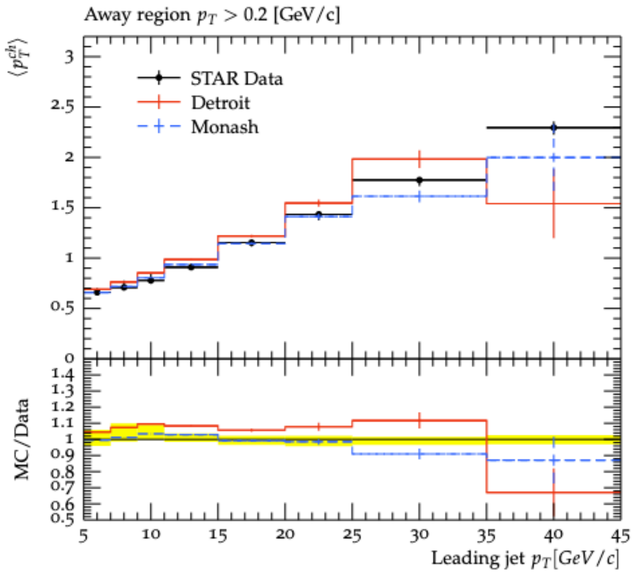
Backup Slides Follow

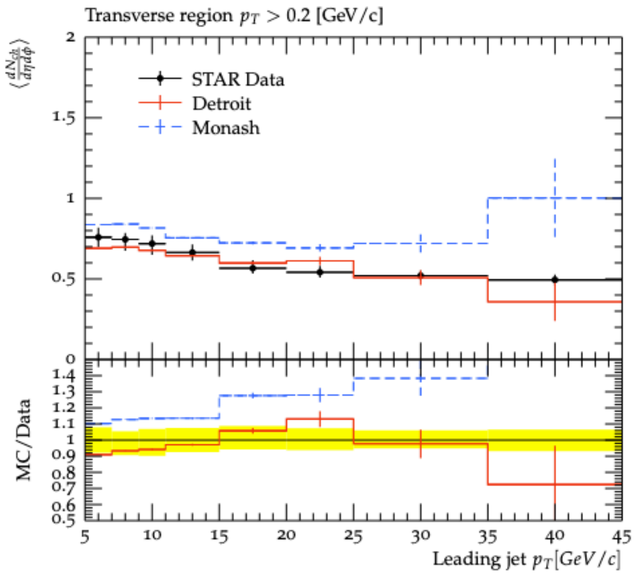
Underling Event @ 200 GeV

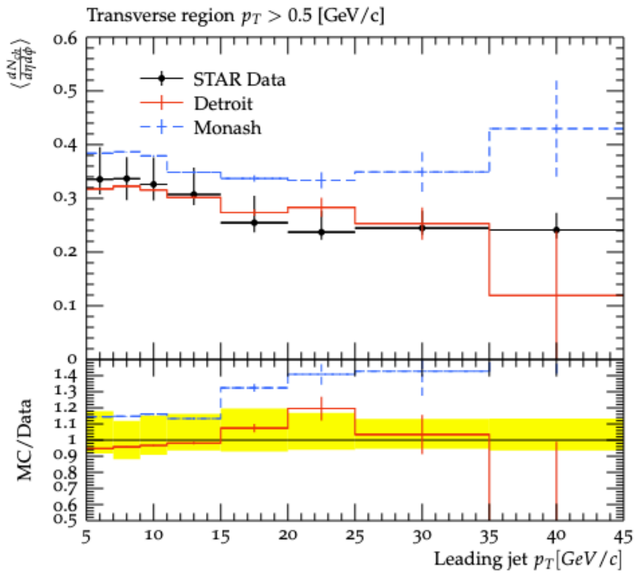


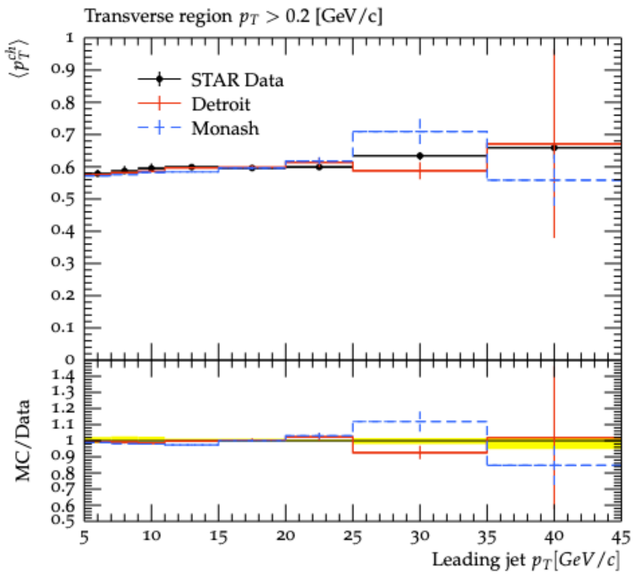


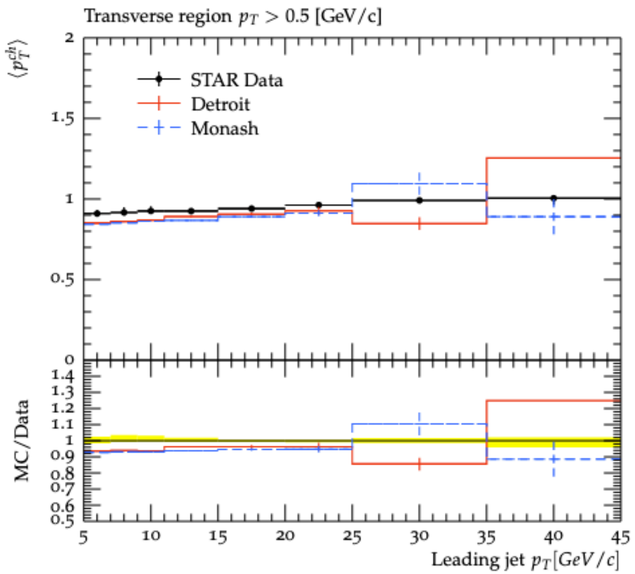




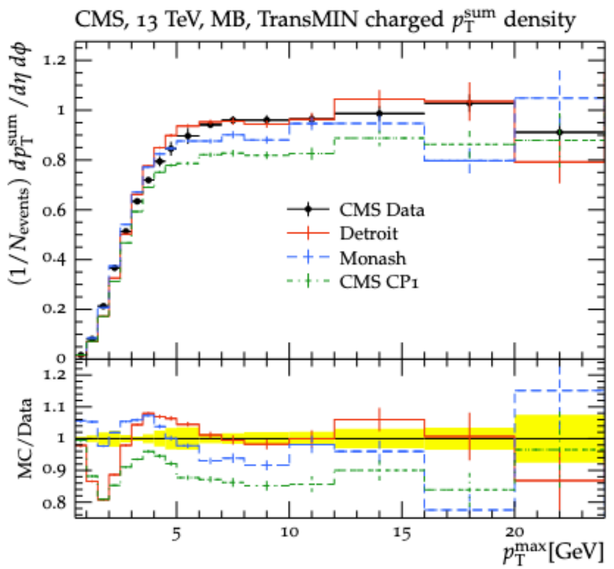


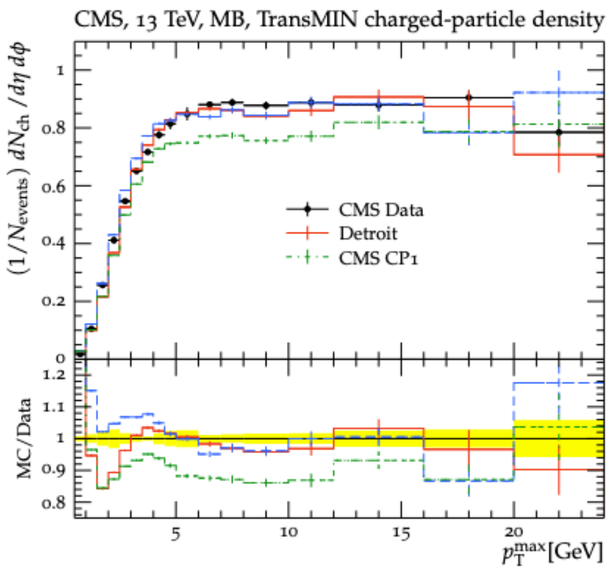


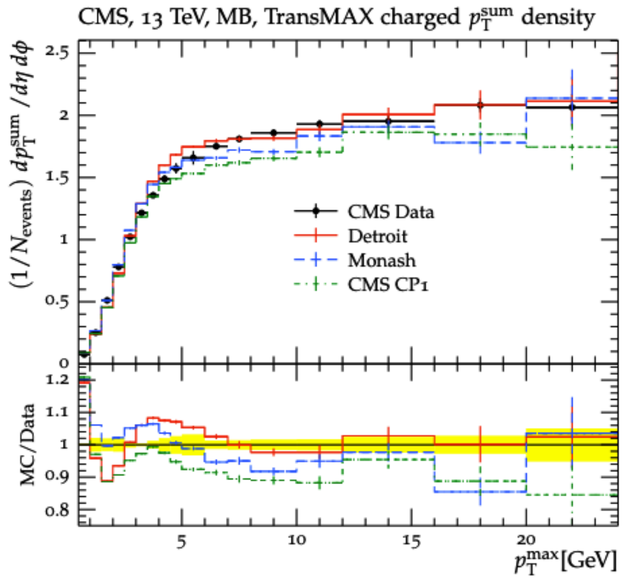


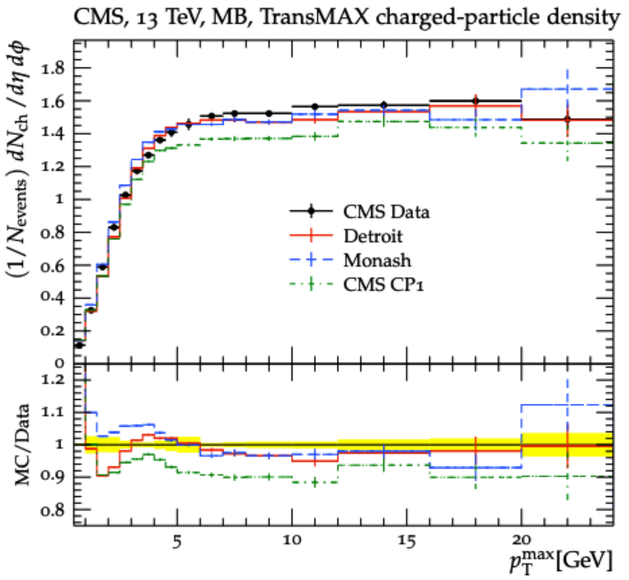


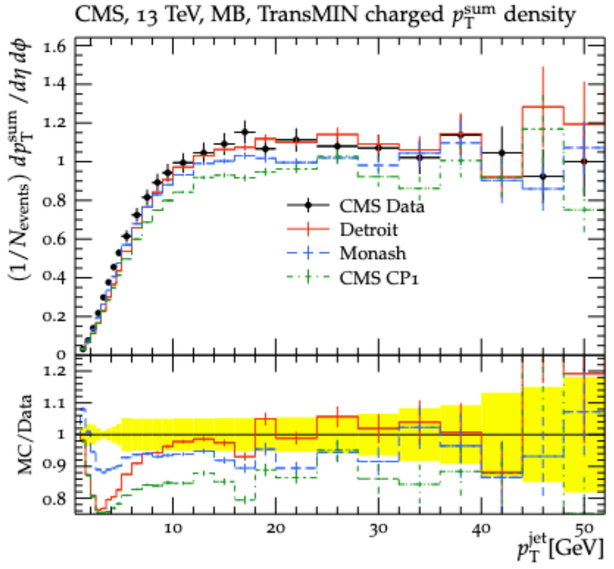
Underling Event @ 13 TeV

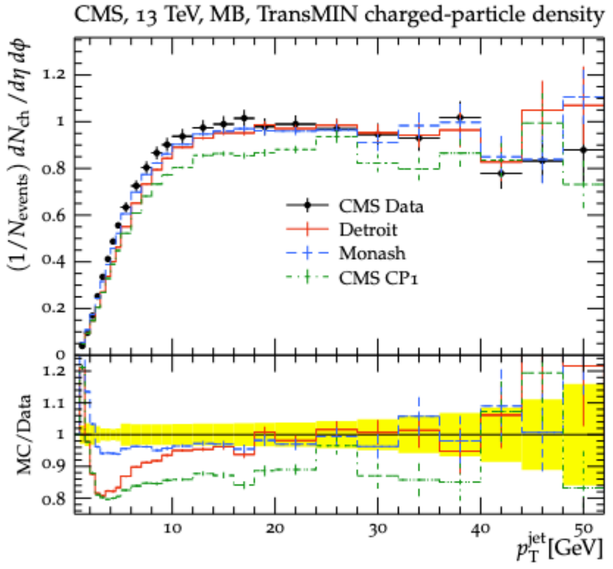


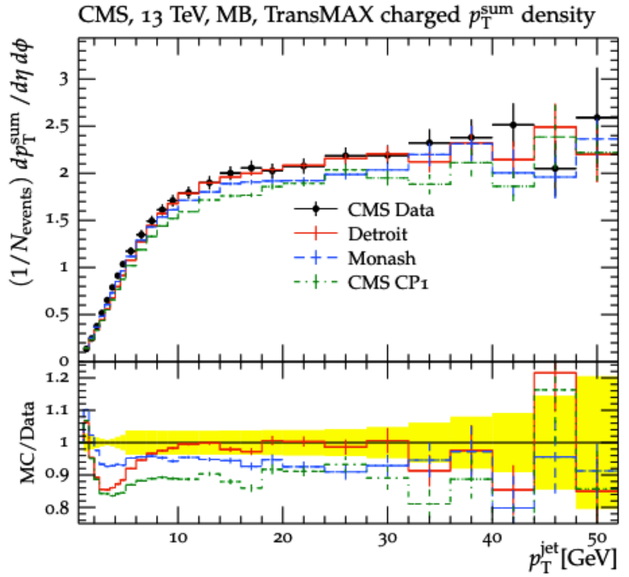


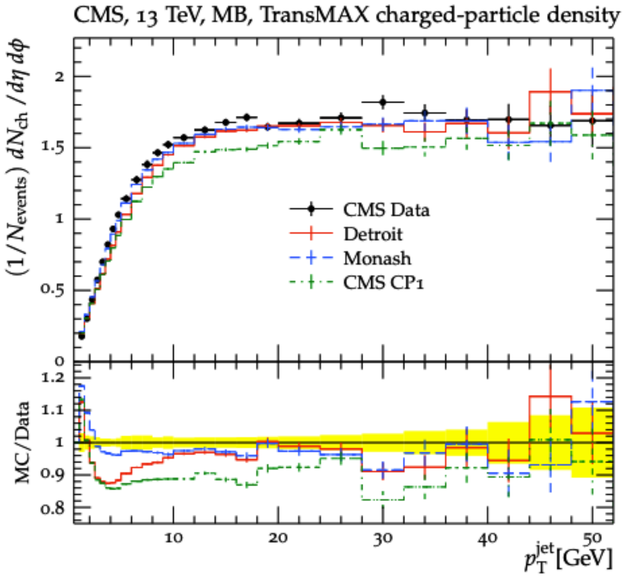




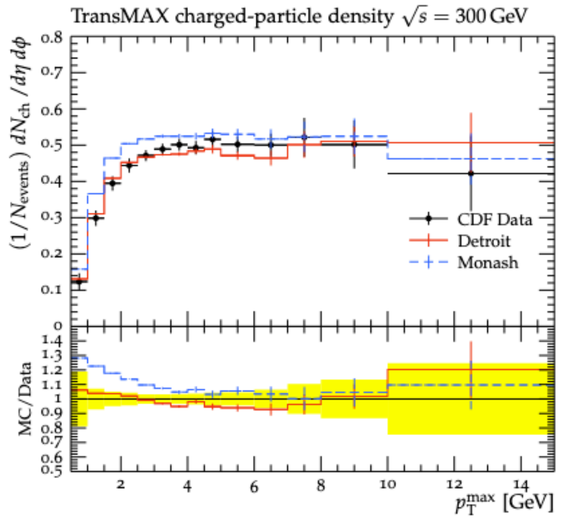


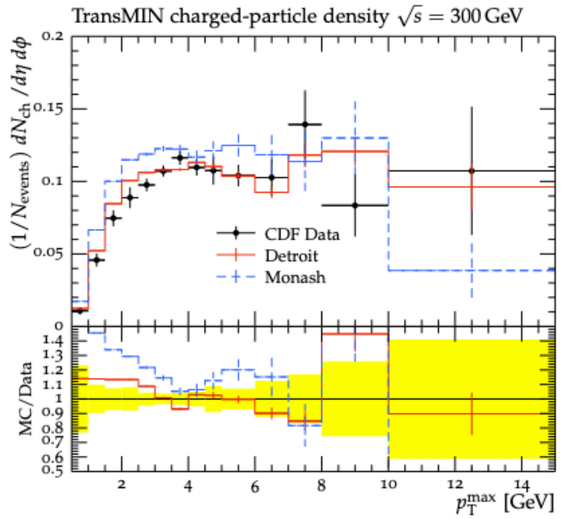


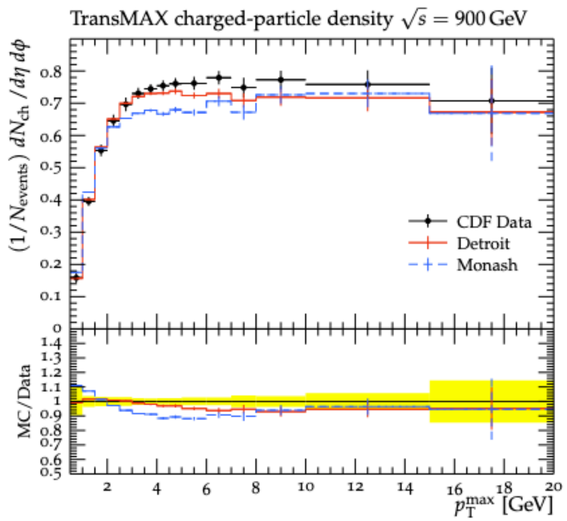


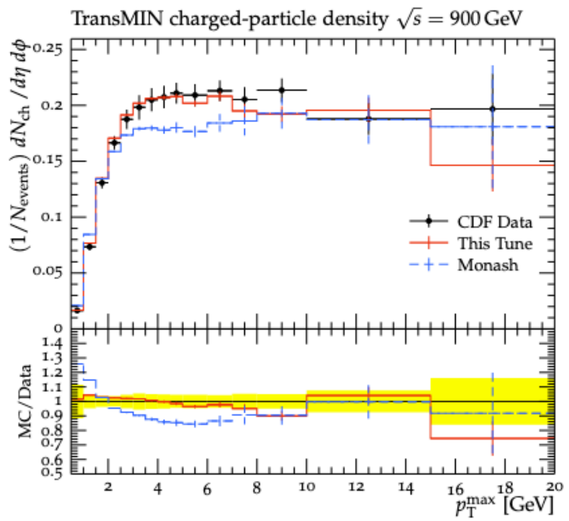


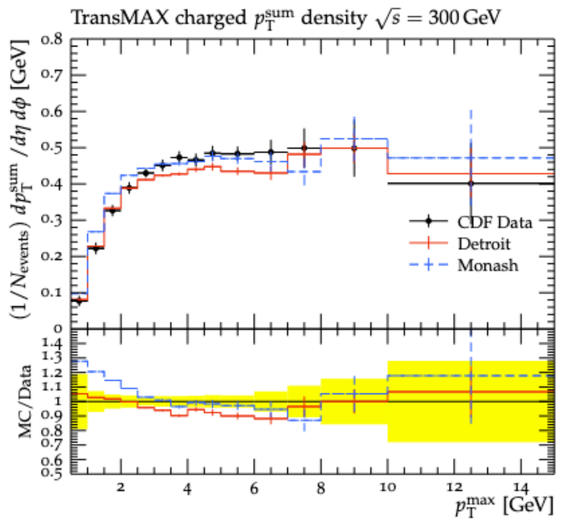
Underling Event: CDF

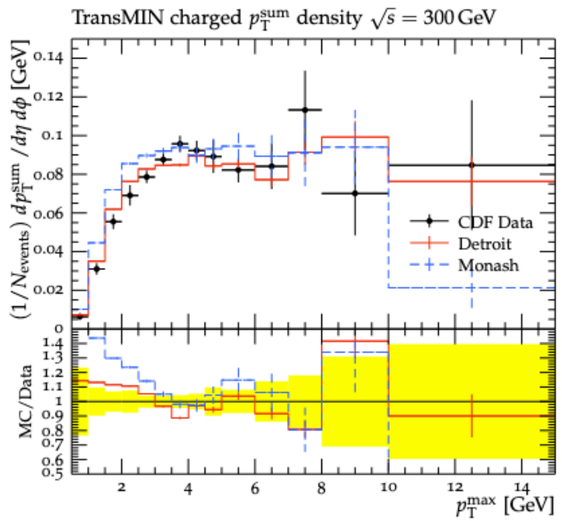


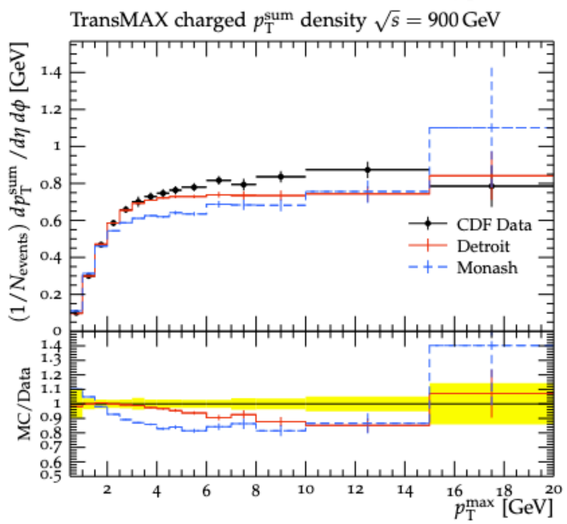


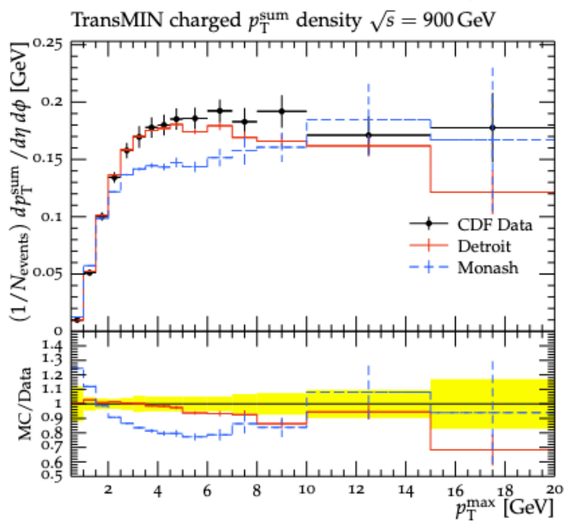




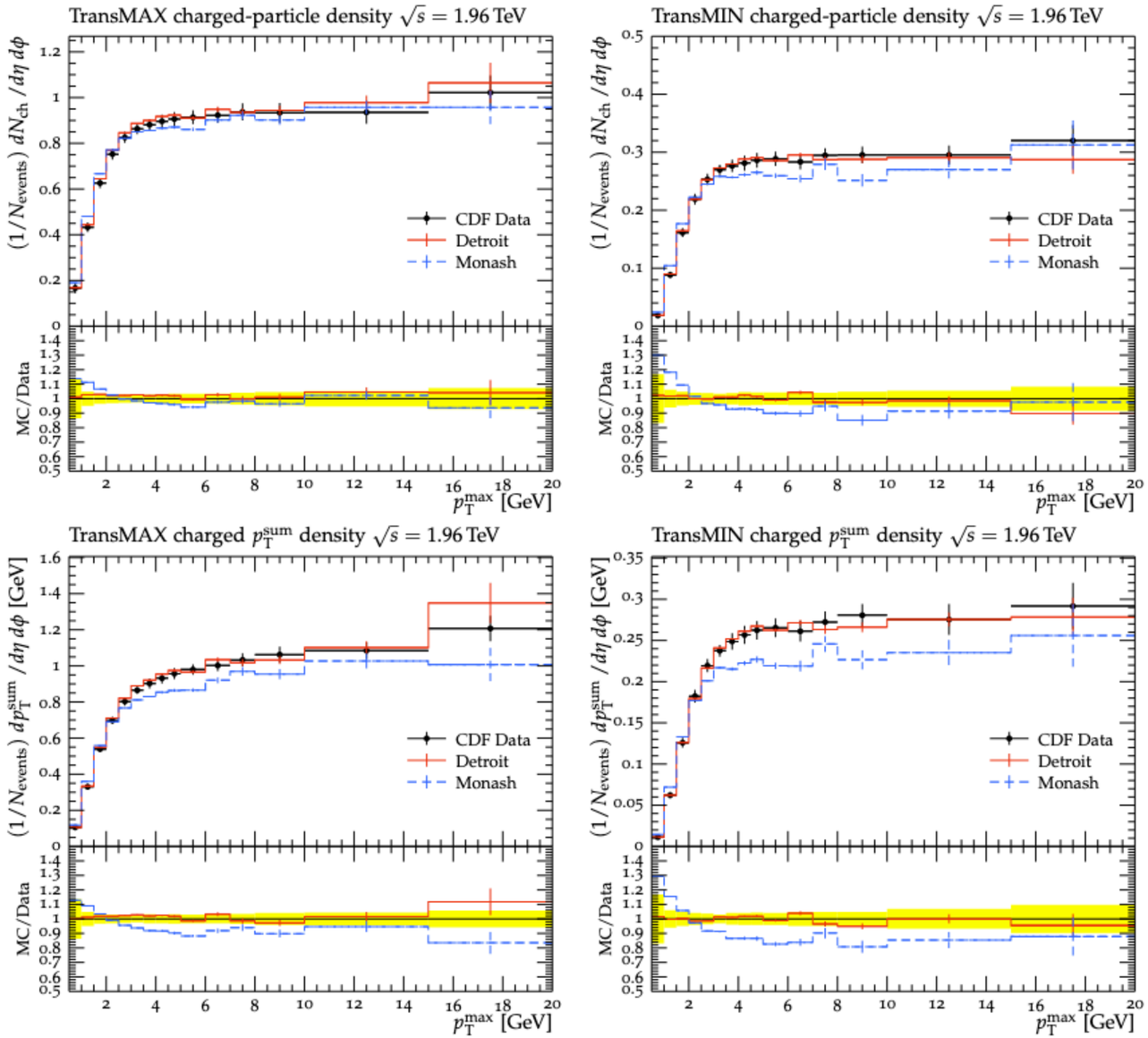




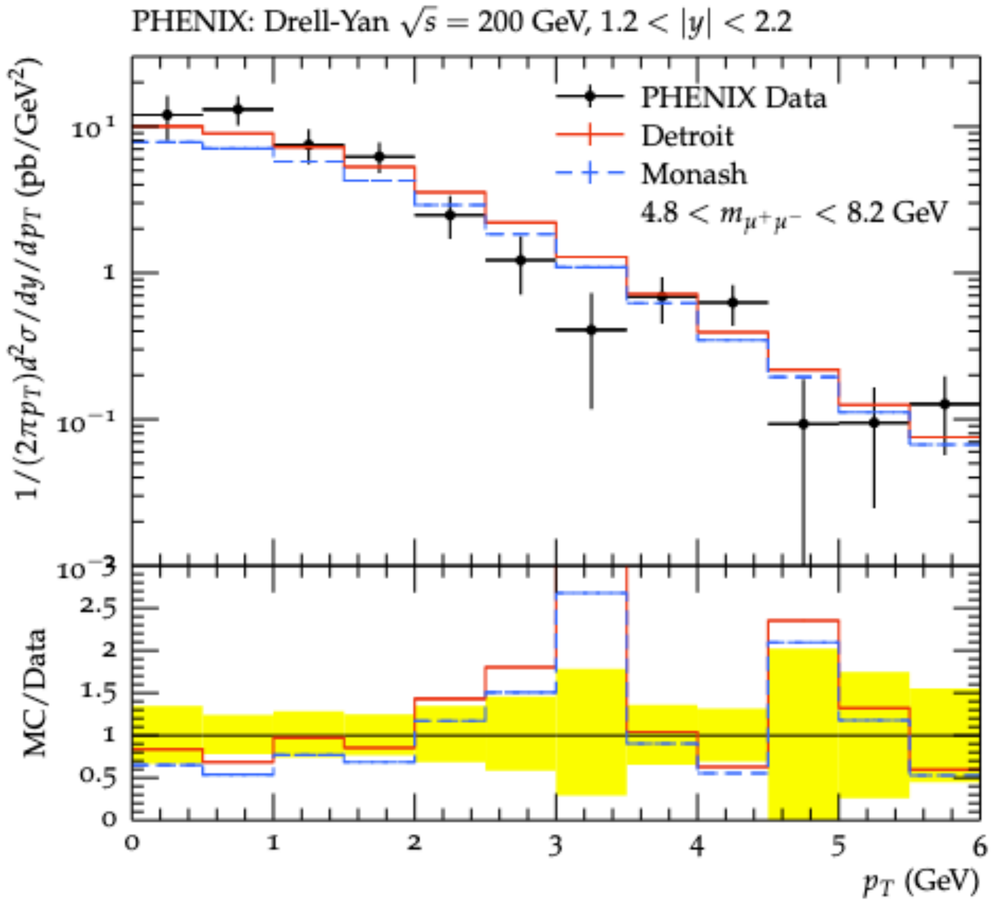


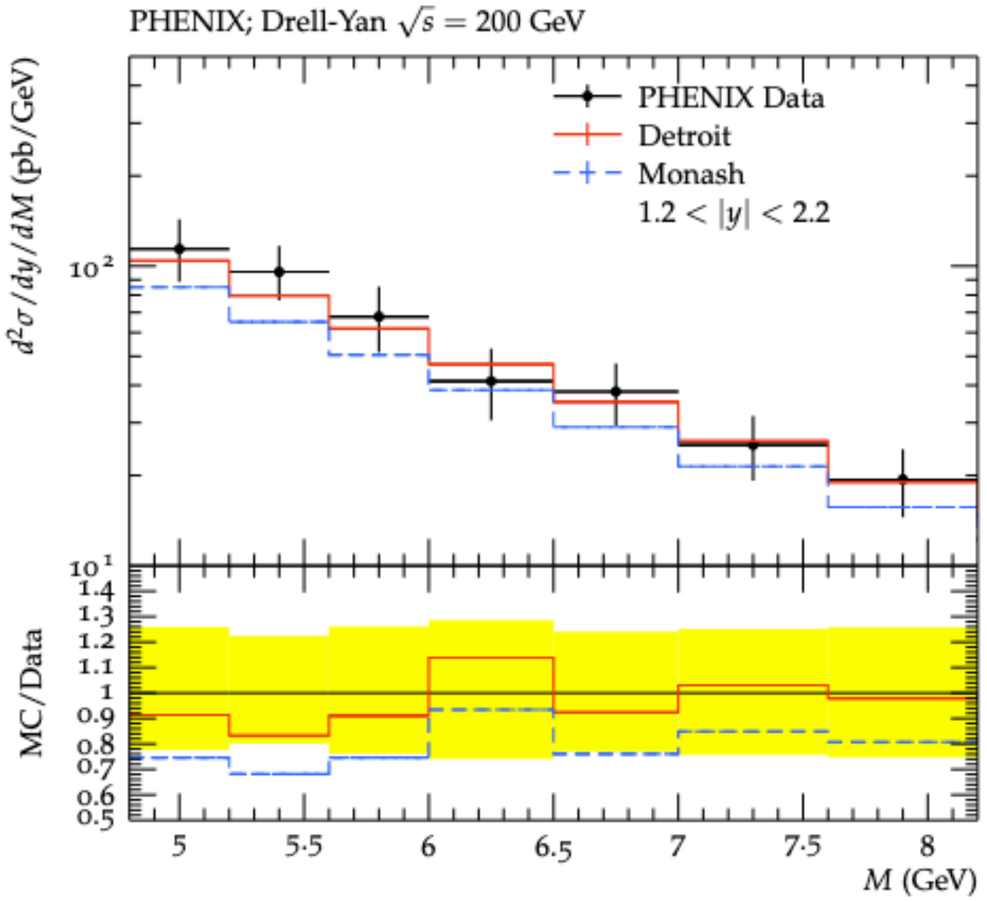


Underling Event: CDF cont.

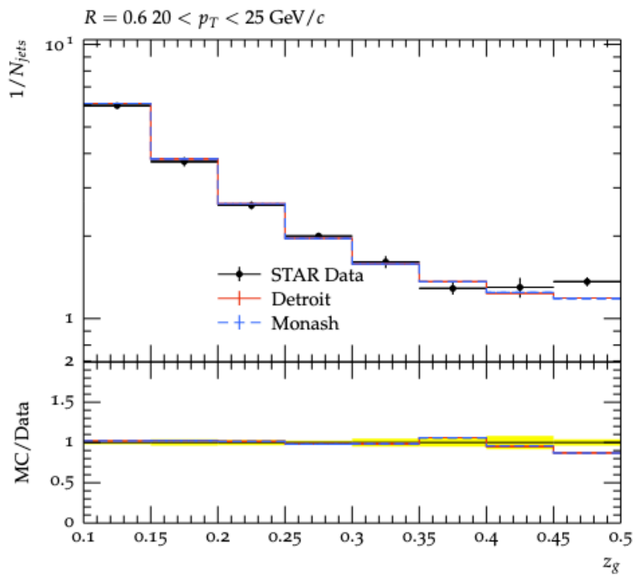


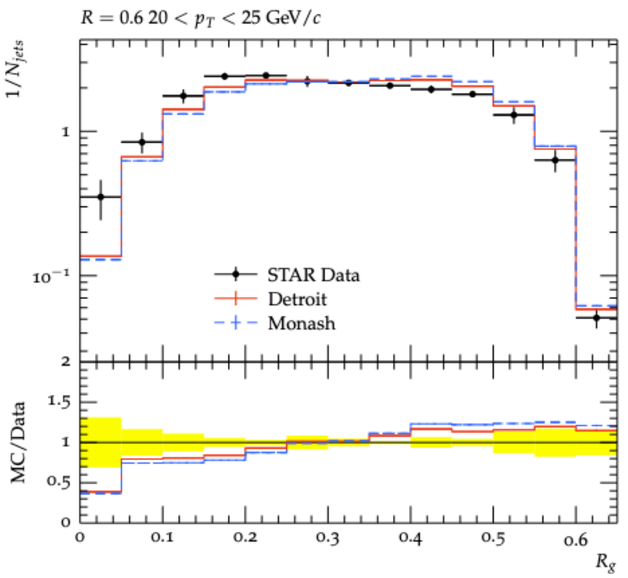
Drell-Yan

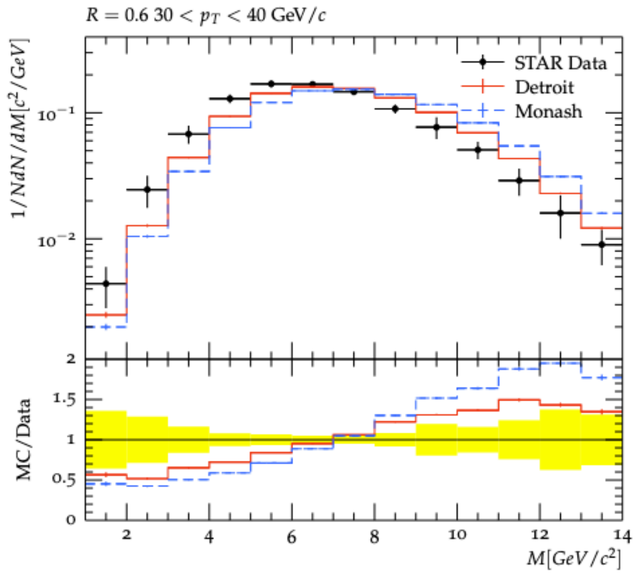

PHENIX: Drell-Yan $\sqrt{s} = 200$ GeV, $1.2 < |y| < 2.2$
PHENIX Data
Detroit
Monash
$4.8 < m_{\mu^+\mu^-} < 8.2$ GeV
$1/(2\pi p_T) d^2\sigma/dy/dp_T$ (pb/GeV^2)
MC/Data
p_T (GeV)


PHENIX; Drell-Yan $\sqrt{s} = 200$ GeV
PHENIX Data
Detroit
Monash
$1.2 < |y| < 2.2$
$d^2\sigma/dy/dM$ (pb/GeV)
MC/Data
M (GeV)

More Jet Observables







MC Errors: Eigentunes

TABLE IV. PYTHIA 8 tune parameter variations for each eigentune.

Tuning Parameter	1+	1-	2+	2-	3+	3-	4+	4-	5+	5-
MultipartonInteractions:pT0Ref (GeV)	1.37	1.43	1.38	1.42	1.44	1.37	1.41	1.40	1.40	1.41
MultipartonInteractions:ecmPow	0.132	0.138	0.135	0.135	0.119	0.150	0.145	0.126	0.148	0.125
MultipartonInteractions:coreRadius	0.74	0.41	0.77	0.41	0.57	0.56	0.57	0.56	0.51	0.60
MultipartonInteractions:coreFraction	0.84	0.72	0.72	0.82	0.78	0.78	0.78	0.78	0.60	0.90
ColourReconnection:range	7.50	3.61	5.38	5.41	5.40	5.40	5.40	5.40	5.41	5.40