

A PYTHIA-8 Underlying Event Tune from RHIC to the LHC

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Supported in part by:



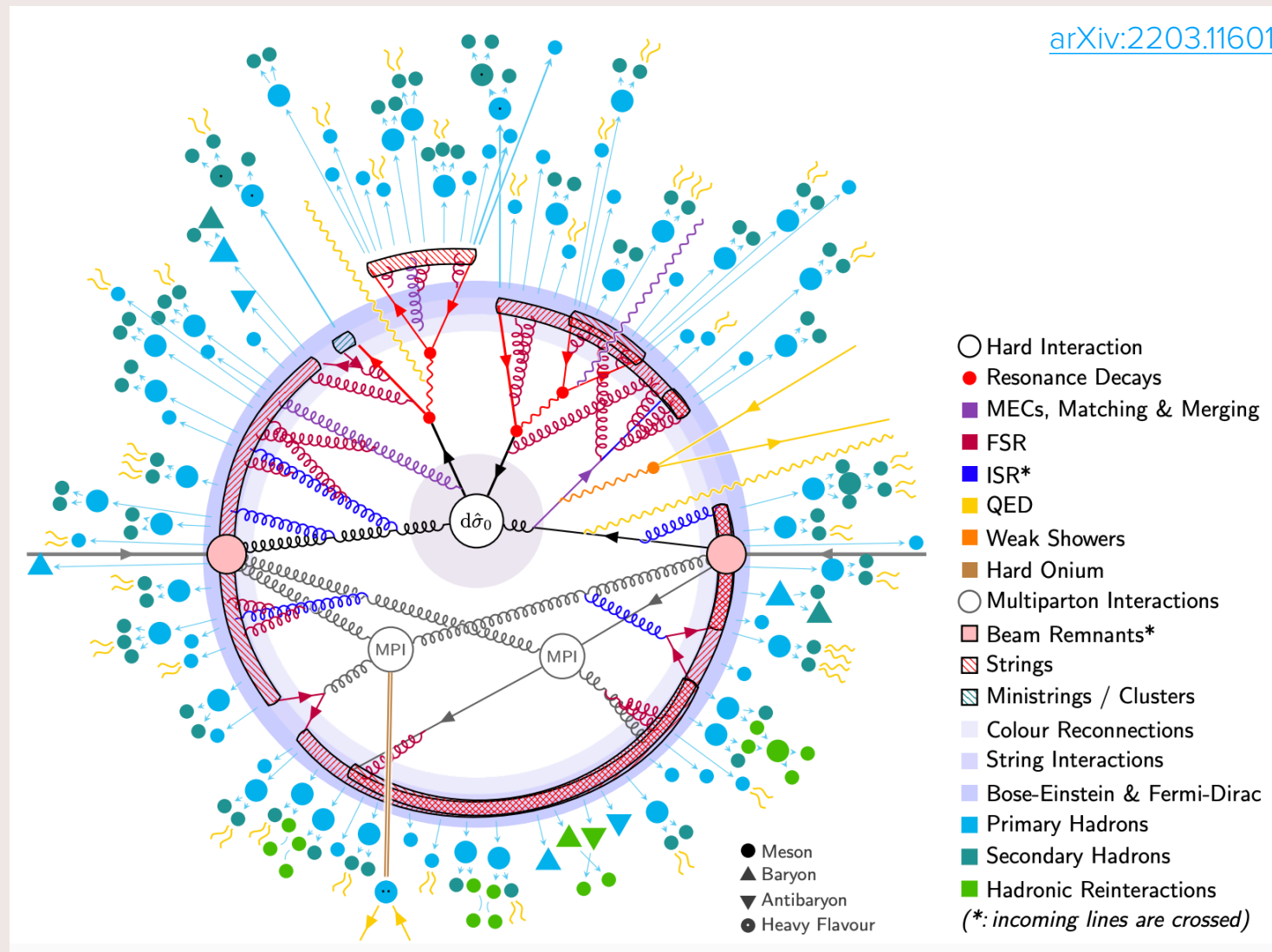
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Monte Carlo event generators



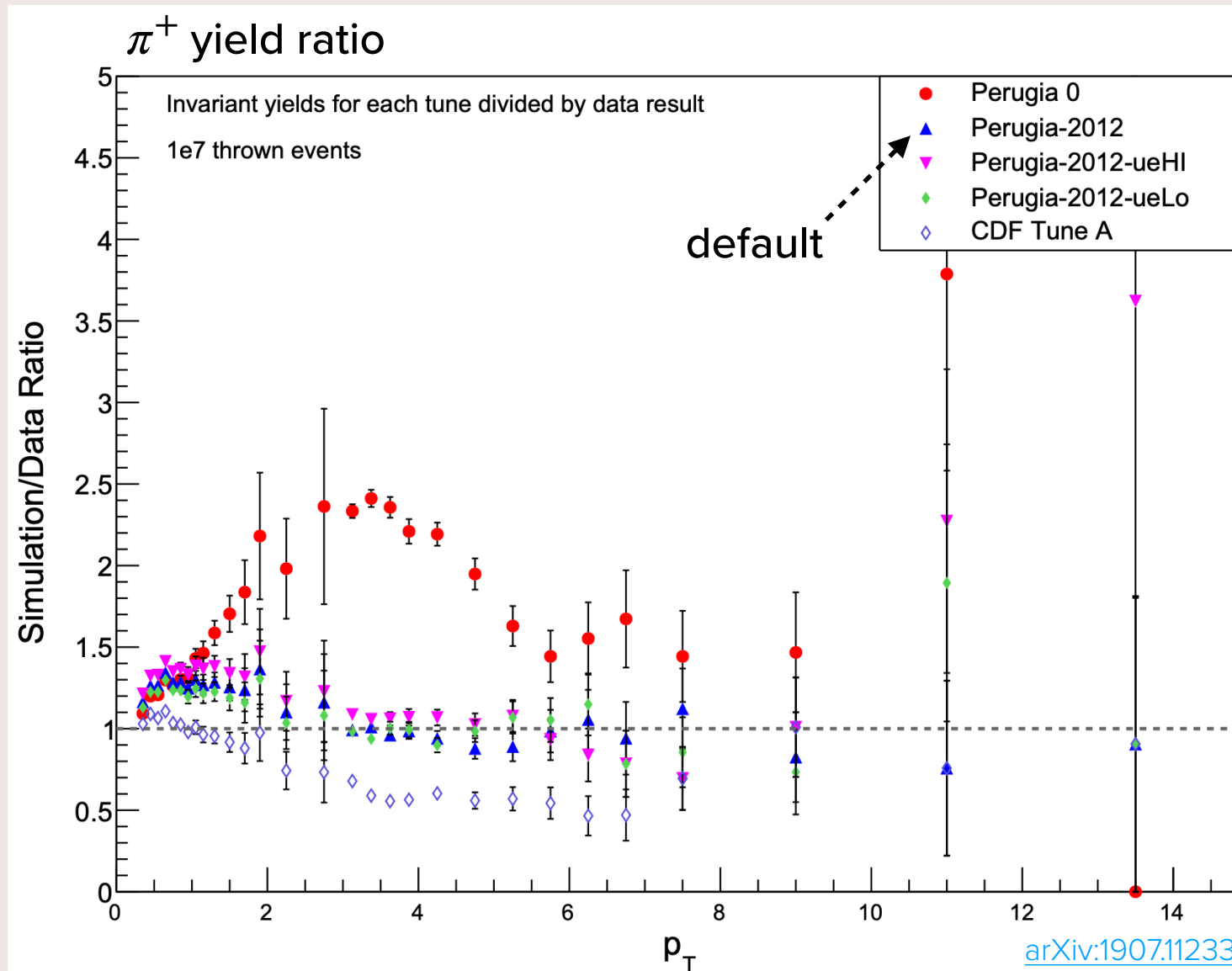
[Image](#)

Full picture of pp collision including soft underlying event is complicated!
Universal applicability requires extrapolation between kinematic regimes →

PYTHIA: $p_{T,0} = p_{T,0}^{\text{ref}} \left(\sqrt{s} / \sqrt{s}_{\text{ref}} \right)^{\text{ecmPow}}$ — phenomenological low- p_T MPI regularizer

Universal?

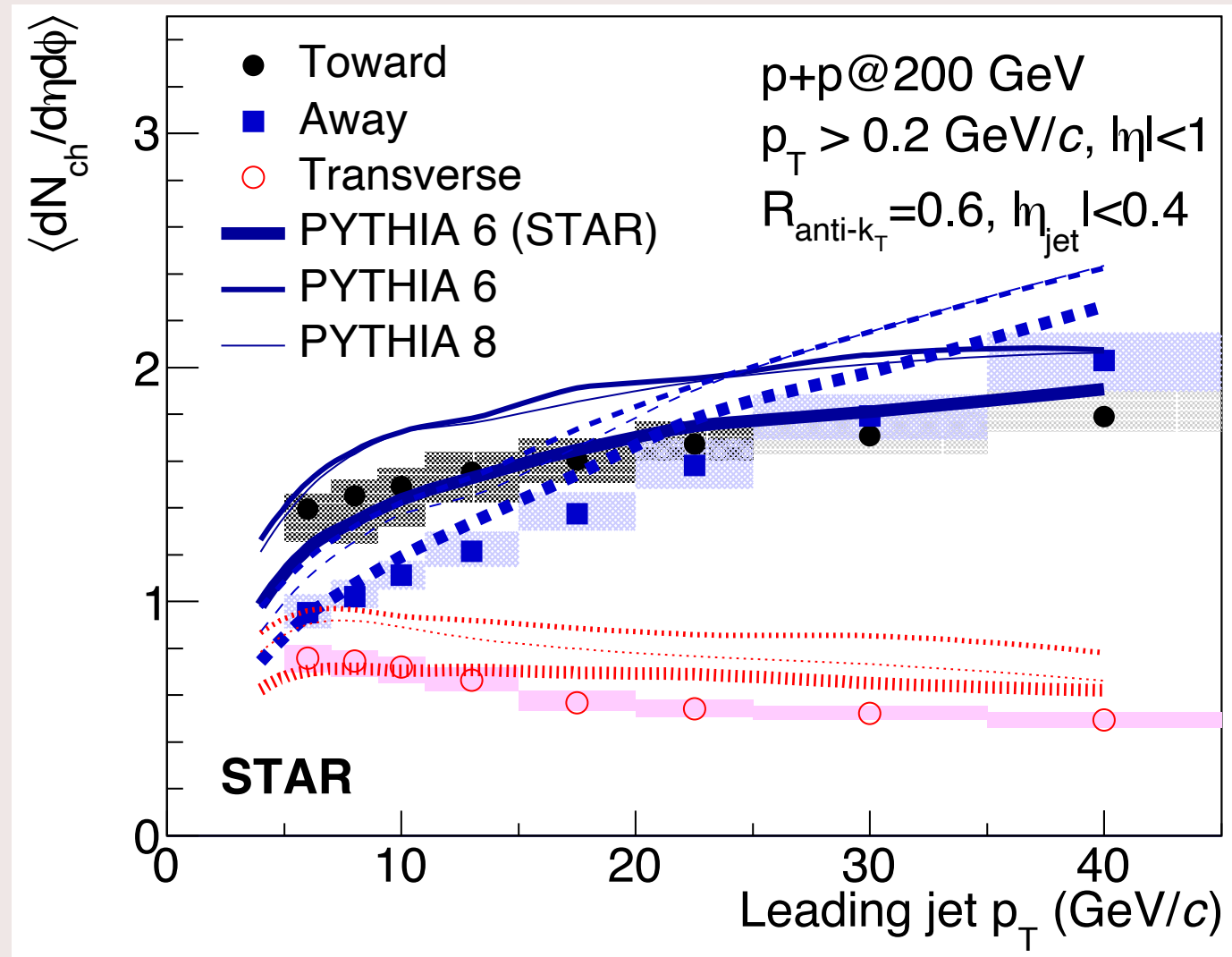
Confronting with RHIC data



Before ecmPow adjusted: PYTHIA-6 default tune disagreed with STAR pion yields by up to 30%

STAR-tuned PYTHIA-6

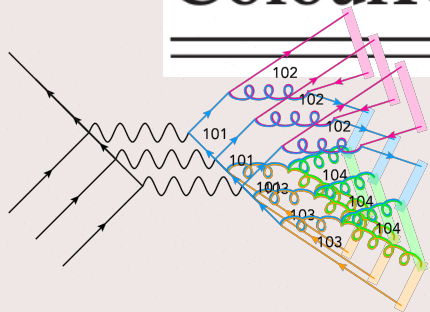
STAR, [PRD 101 \(2020\) 5, 052004](#)



After: “STAR-tuned” PYTHIA-6 (ecmPow: 0.240 $\rightarrow$ 0.213) in excellent agreement with underlying event (UE) observables (better than PYTHIA-8!)

PYTHIA-8 tuning parameters

Setting	Monash	New
PDF:pSet	NNPDF 2.3	NNPDF 3.1
MultipartonInteractions:ecmRef	7 TeV	200 GeV
MultipartonInteractions:bprofile	exp overlap	double Gauss
Tuning Parameter	Monash	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	.0–9.0



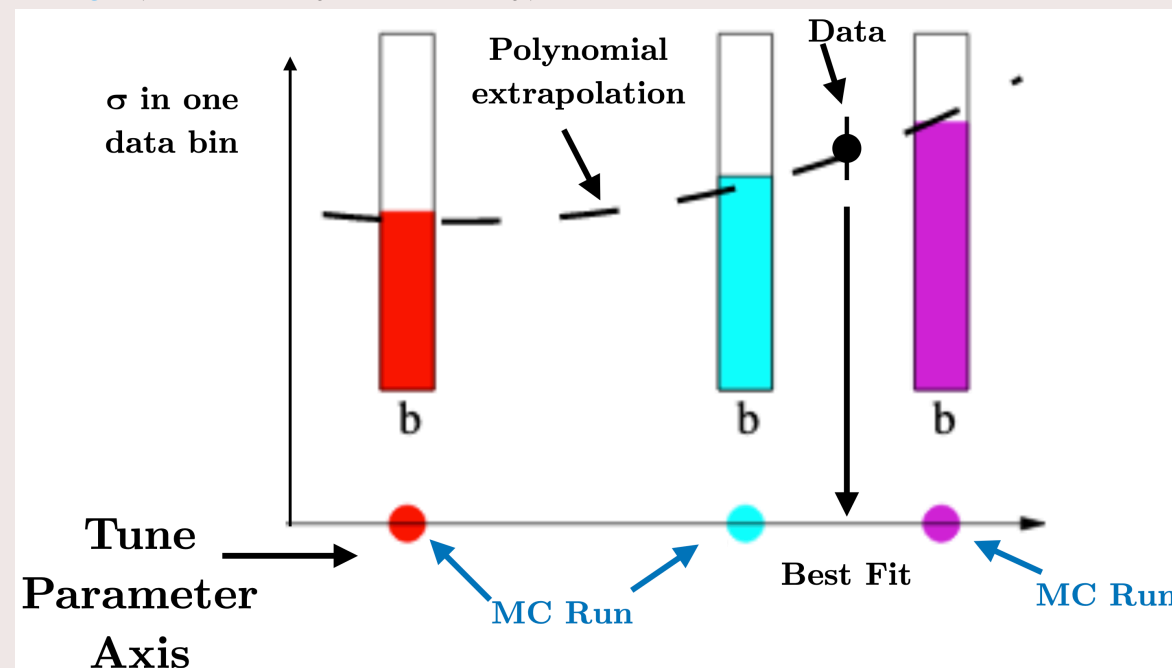
Tuned exclusively using MPI parameters

$\sqrt{s}_{\text{ref}}$ set to RHIC energy, for minimal extrapolation

Tuning procedure

PROFESSOR

[Image](#) (modified by Matt Kelsey)



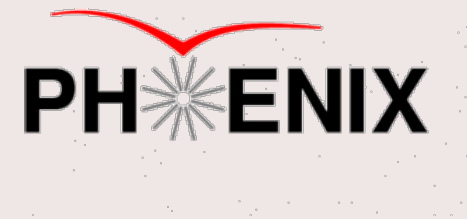
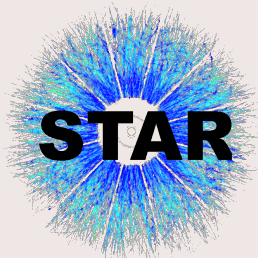
Randomly sample param. values → run event gen. → histograms for all observables

$$\text{Interpolate: } \text{MC}_b(\mathbf{p}) \approx f^{(b)}(\mathbf{p}) = \alpha_0^{(b)} + \sum_i \beta_i^{(b)} p'_i + \sum_{i \leq j} \gamma_{ij}^{(b)} p'_i p'_j$$

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

Data used for tuning

Experiment	$\sqrt{s}$ (GeV)	Observable	Reference
STAR	200	$\pi^\pm$ cross sections vs p_T	PLB 637 (2006) 161-169
PHENIX	200	Dimuon pairs from Drell-Yan vs di-muon p_T	PRD 99 (2019) 7, 072003
STAR	200	Average charged particle multiplicities and p_T vs leading jet p_T in the forward, transverse, and away regions	PRD 101 (2020) 5, 052004
CDF	300, 900, 1960	Charge particle density and $\sum p_T$ vs leading hadron p_T in transverse region	PRD 92 (2015) 9, 092009
STAR	200	SoftDrop groomed jet substructure (z_g and R_g)	PLB 811 (2020) 135846
STAR	200	Inclusive and groomed jet mass	PRD 104 (2021) 5, 052007



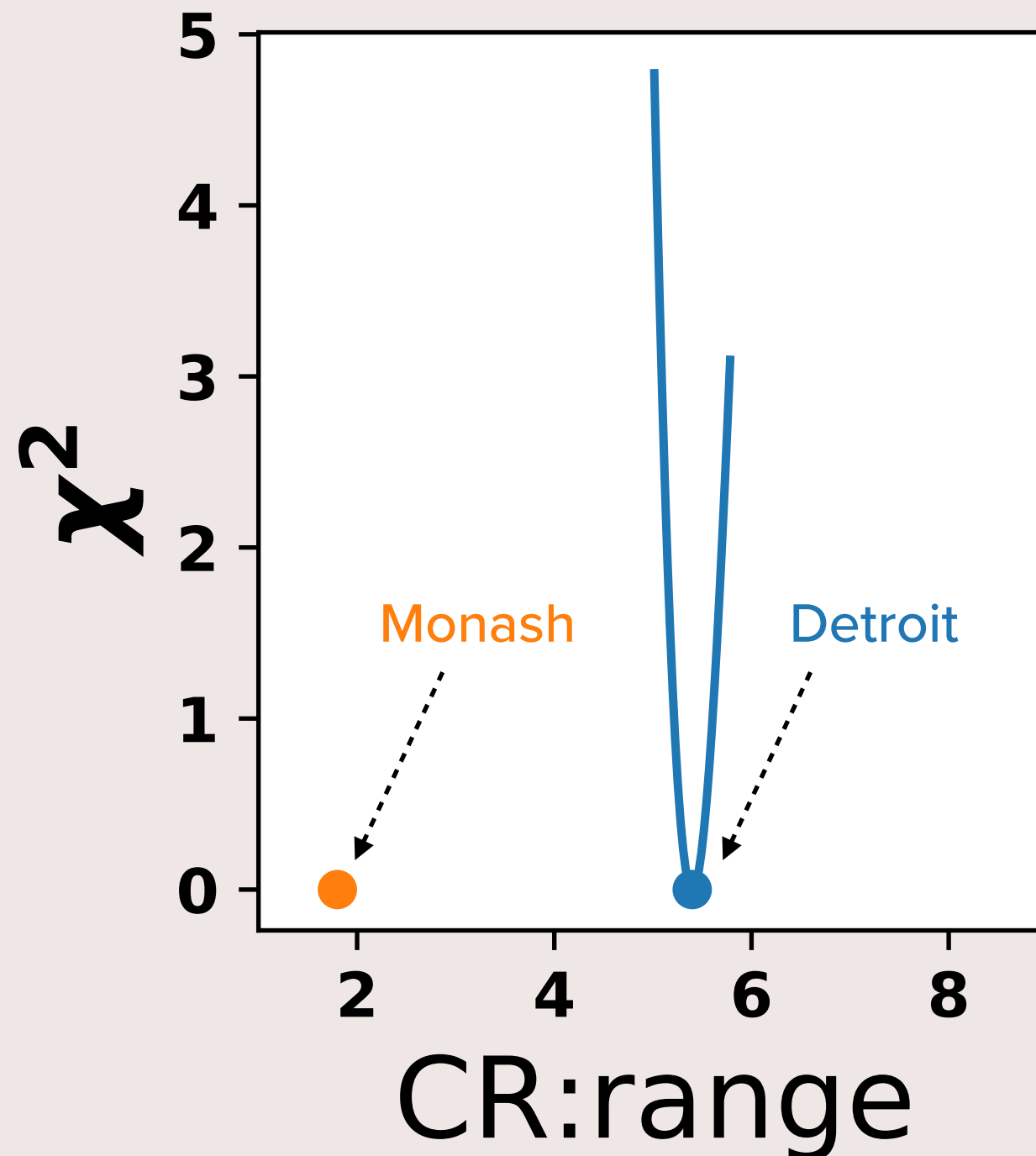
A representative sample of hard and soft physics observables from RHIC and Tevatron energies

STAR analyses now included in RIVET¹!

<https://github.com/star-bnl/star-PYTHIA8-tune>

Introducing the “Detroit” Tune

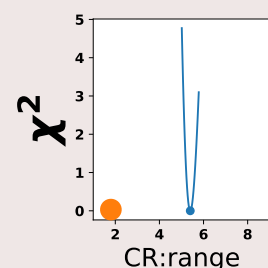
Aguilar, Chang, Kunnawalkam Elayavalli, Fatemi, He, Ji, Kalinkin, Kelsey, IAM, Verkest, [PRD 105 \(2022\) 1, 016011](#)



ColourReconnection:range
1.8 → 5.4

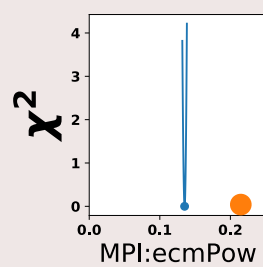
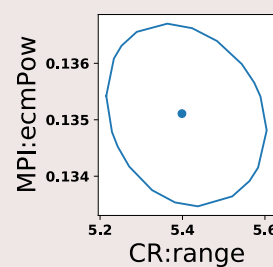
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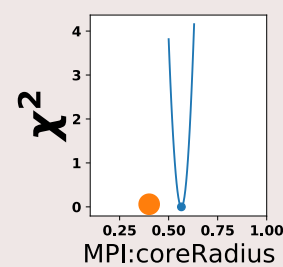
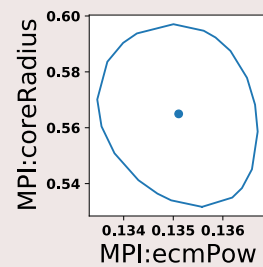
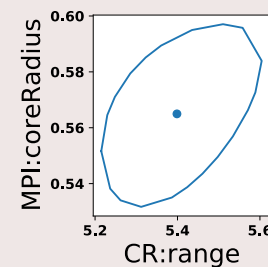


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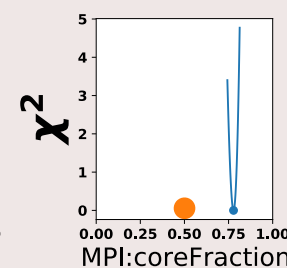
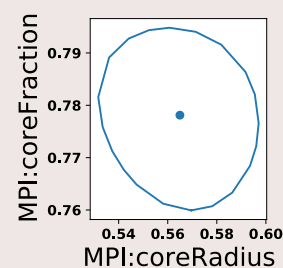
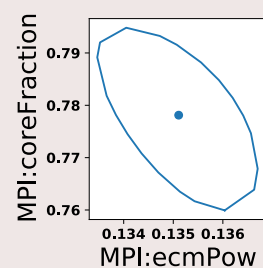
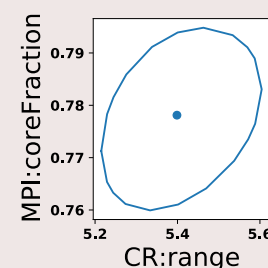
Global $\chi^2/\text{ndf} = 611/493$



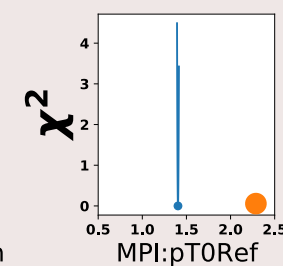
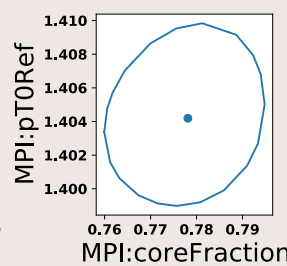
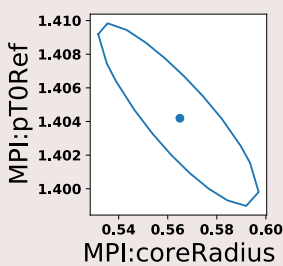
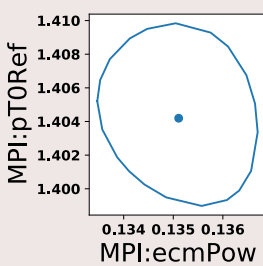
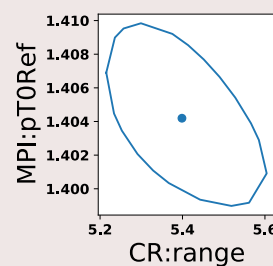
MultipartonInteractions:ecmPow
0.215 → 0.135



MultipartonInteractions:coreRadius
0.4 → 0.56



MultipartonInteractions:coreFraction
0.5 → 0.78

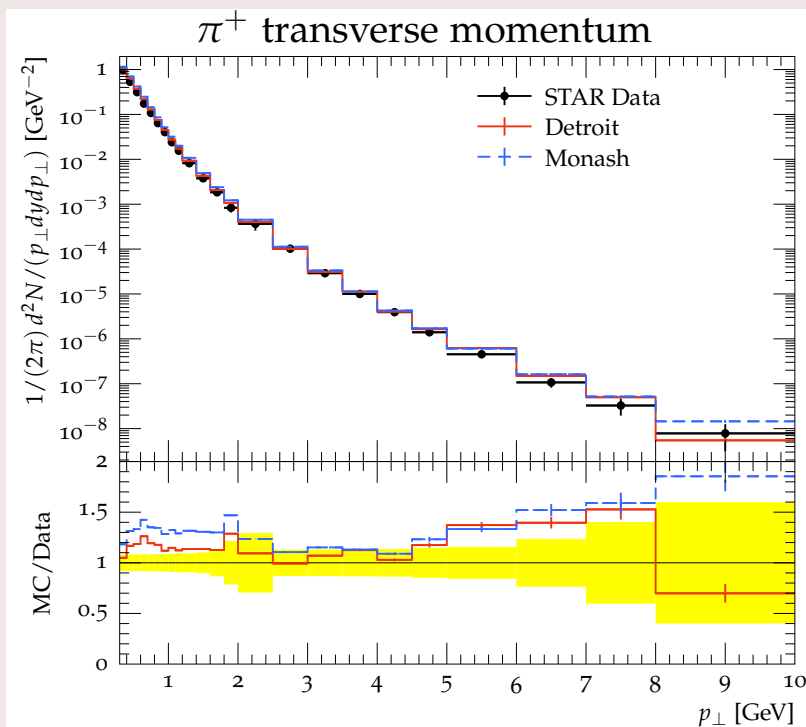
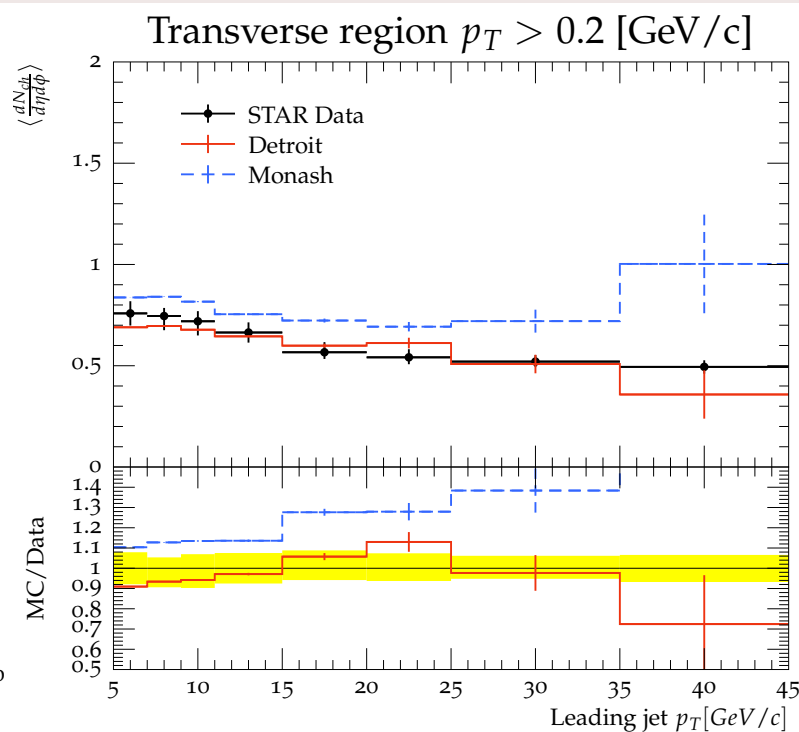
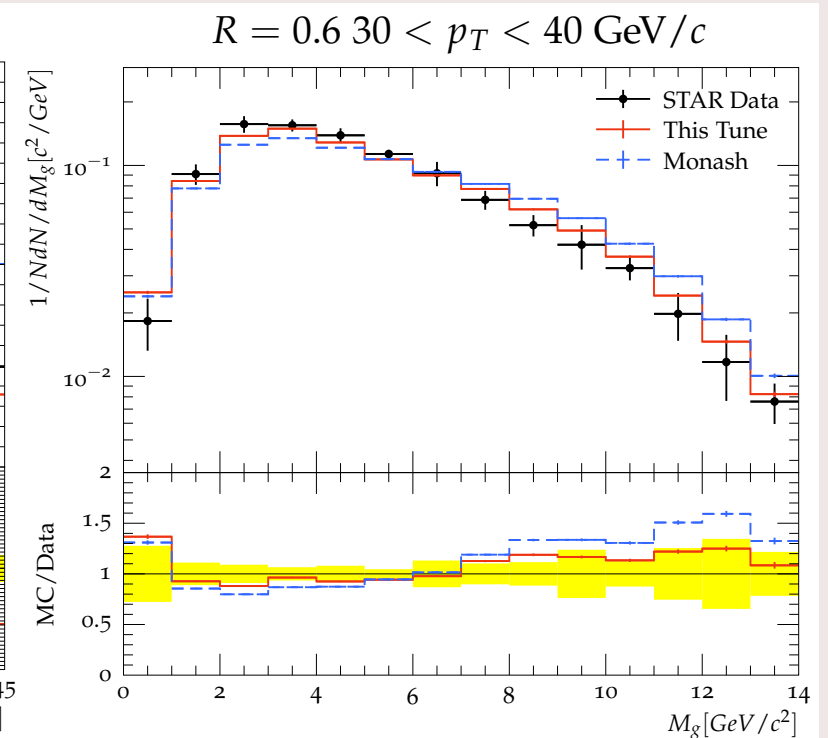


MultipartonInteractions:pT0Ref
2.28 → 1.40 GeV

representative sample

Comparison to data

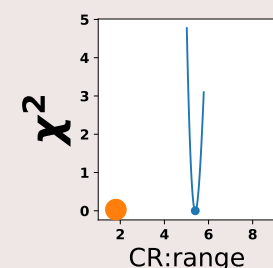
RHIC – 200 GeV

STAR, [PLB 637 \(2006\) 161-169](#)STAR, [PRD 101 \(2020\) 5, 052004](#)STAR, [PRD 104 \(2021\) 5, 052007](#)

Detroit outperforms **Monash** consistently for UE observables and low- p_T yields as expected, but also for jet substructure observables

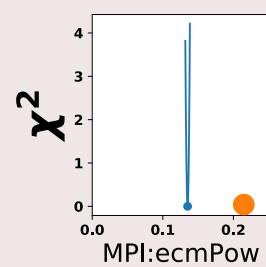
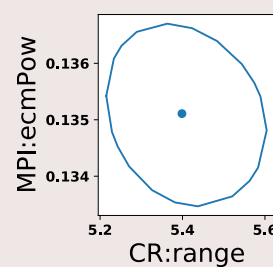
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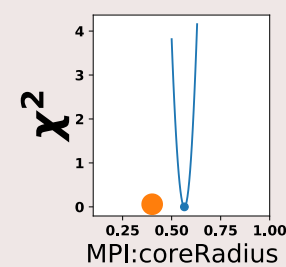
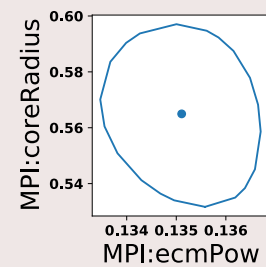
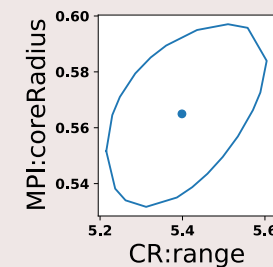


ColourReconnection:range
1.8 → 5.4

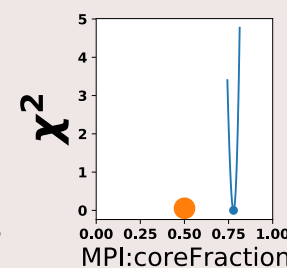
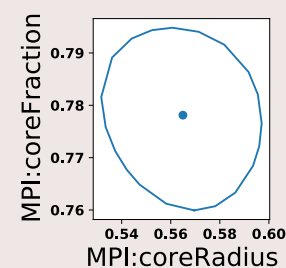
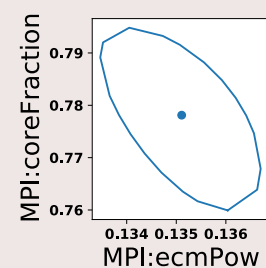
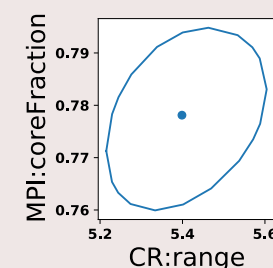
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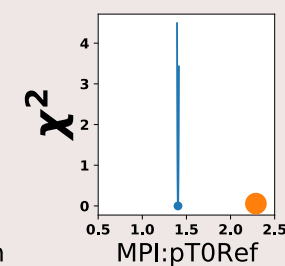
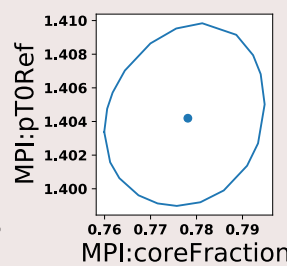
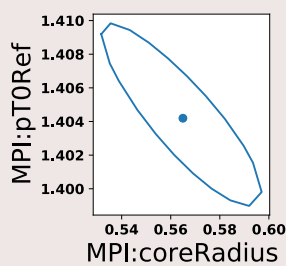
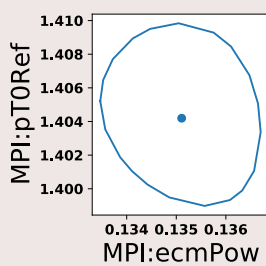
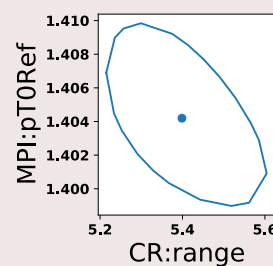
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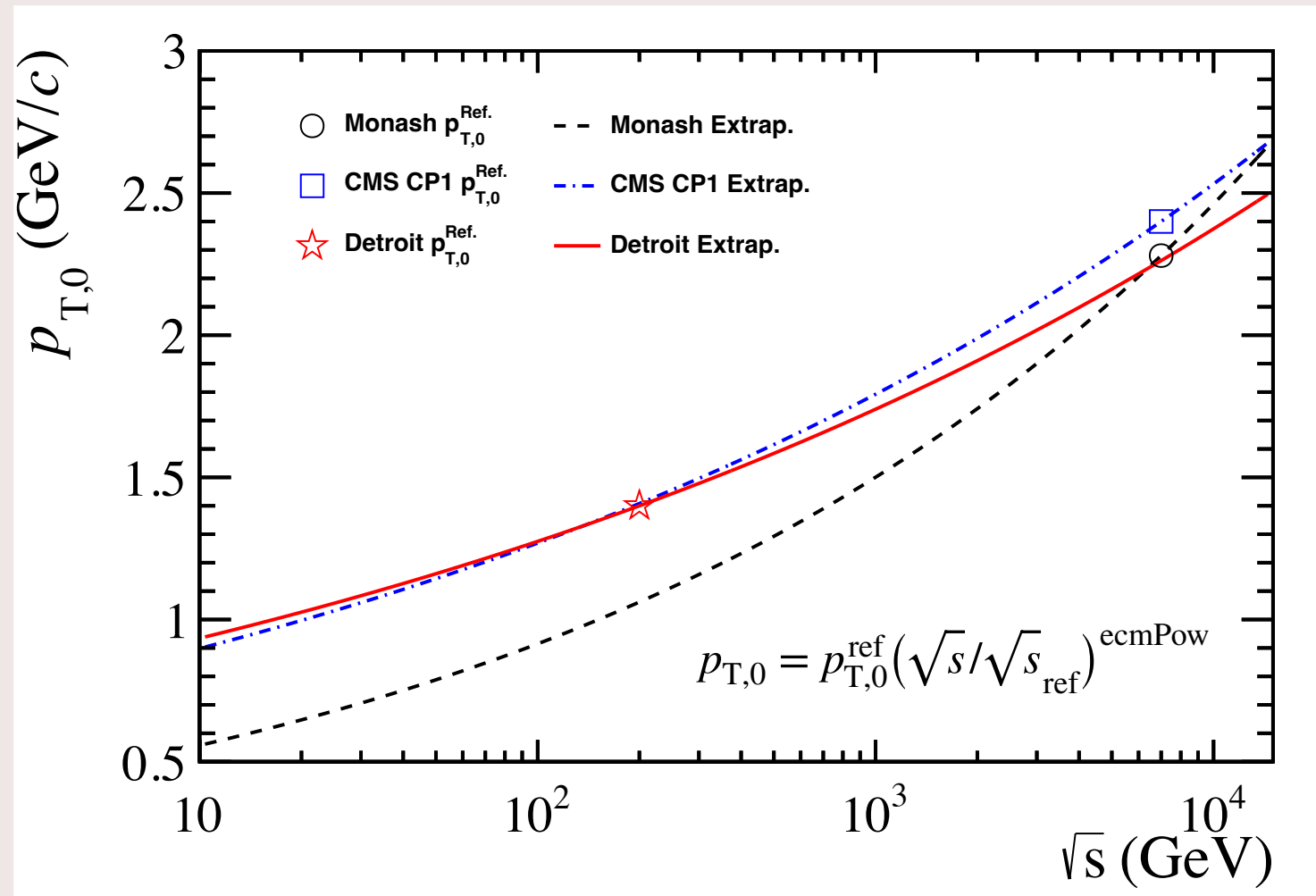
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Energy extrapolation

Aguilar, Chang, Kunnawalkam Elayavalli, Fatemi, He, Ji, Kalinkin, Kelsey, IAM, Verkest, [PRD 105 \(2022\) 1, 016011](#)



Disagreement with Monash $\sim 30\%$ at 200 GeV/c

CMS CP1¹ tune's $p_{T,0}$ varies more rapidly with energy

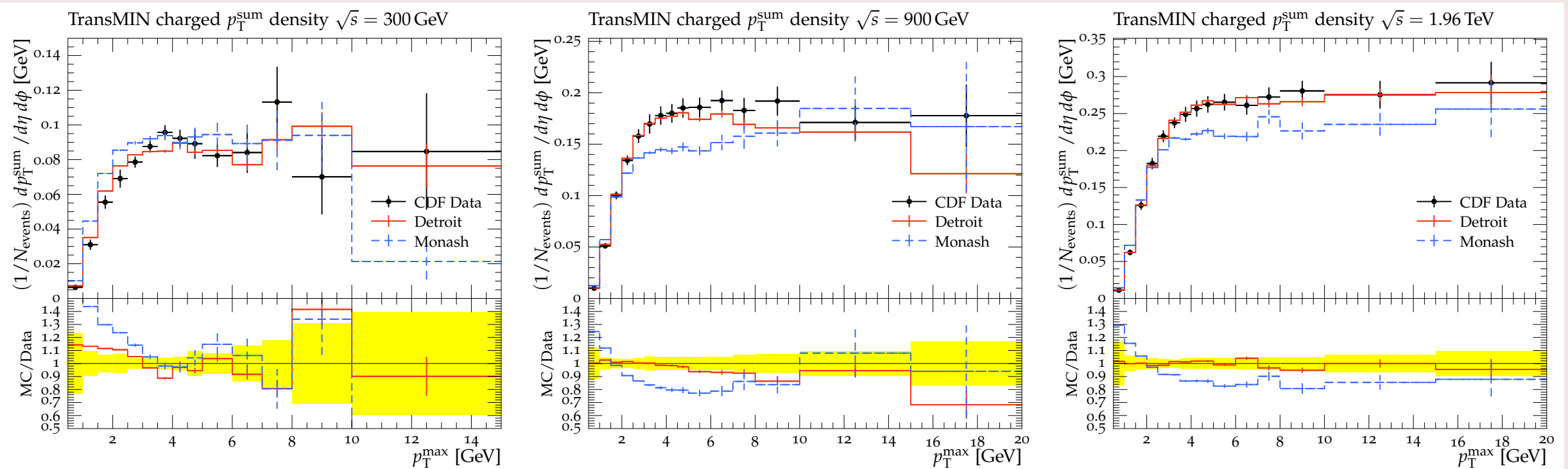
¹CMS, [EPJC 80 \(2020\) 1, 4](#)

Comparison to data

Tevatron — 0.3 to 1.96 TeV



CDF, [PRD 92 \(2015\) 9, 092009](#)



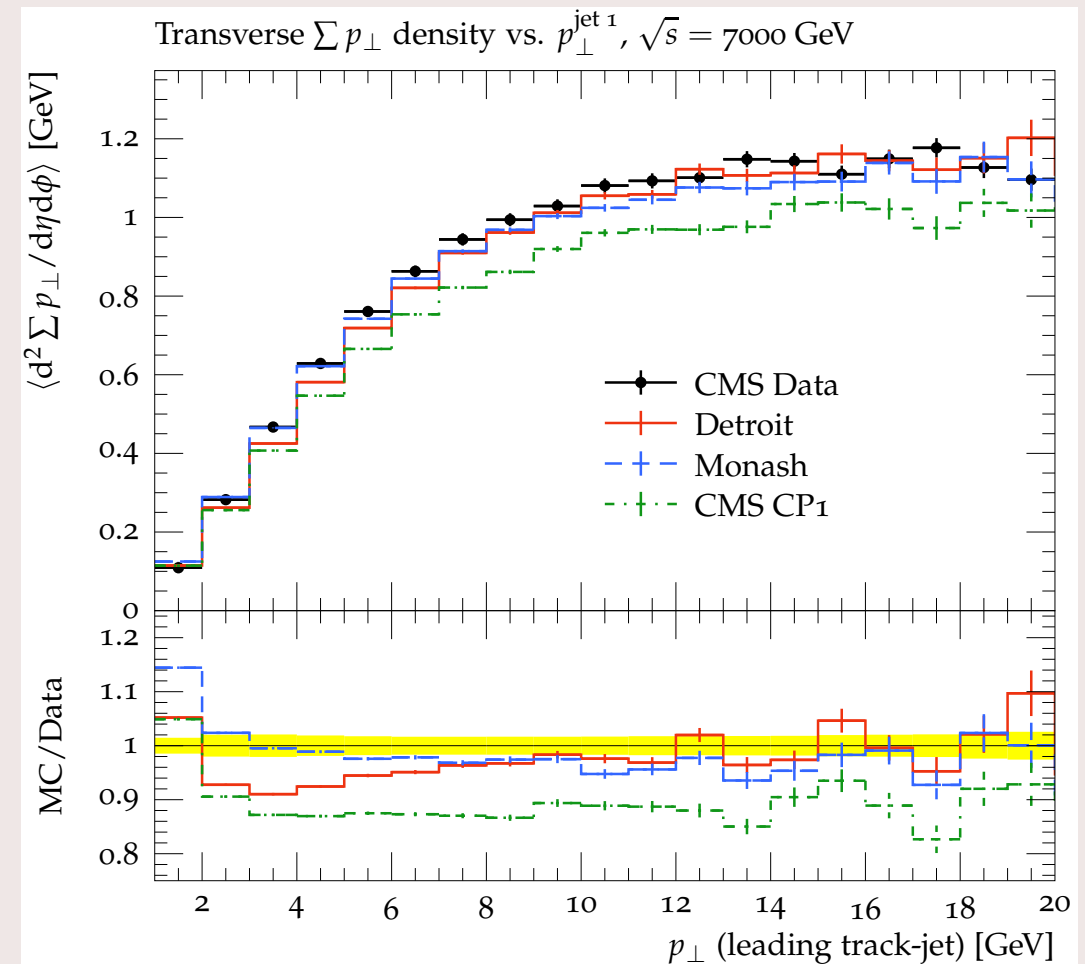
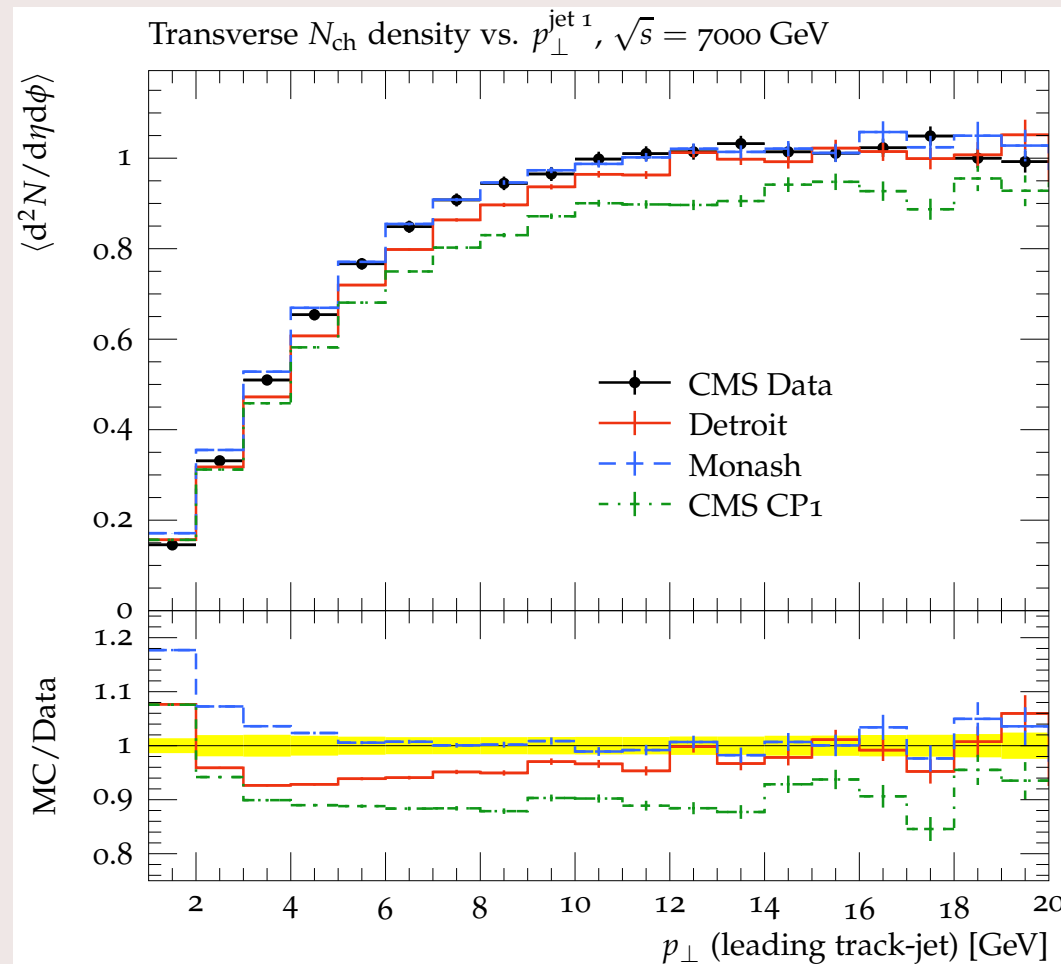
Detroit: excellent agreement with CDF data across wide range of energy

Monash: disagreement at, respectively, low-, mid-, and high- p_T^{max} as $\sqrt{s}$ increases

Comparison to data

LHC – 7 TeV

CMS, [JHEP 09 \(2011\) 109](#)

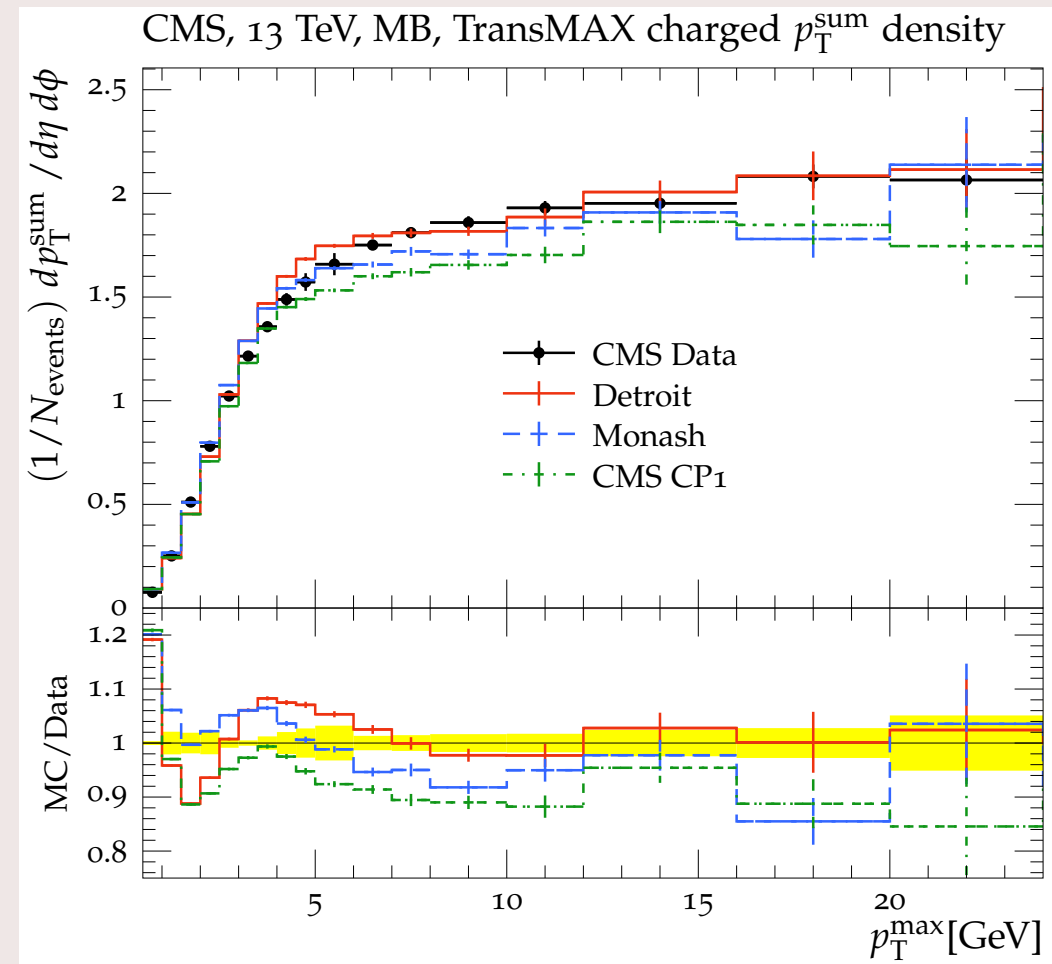
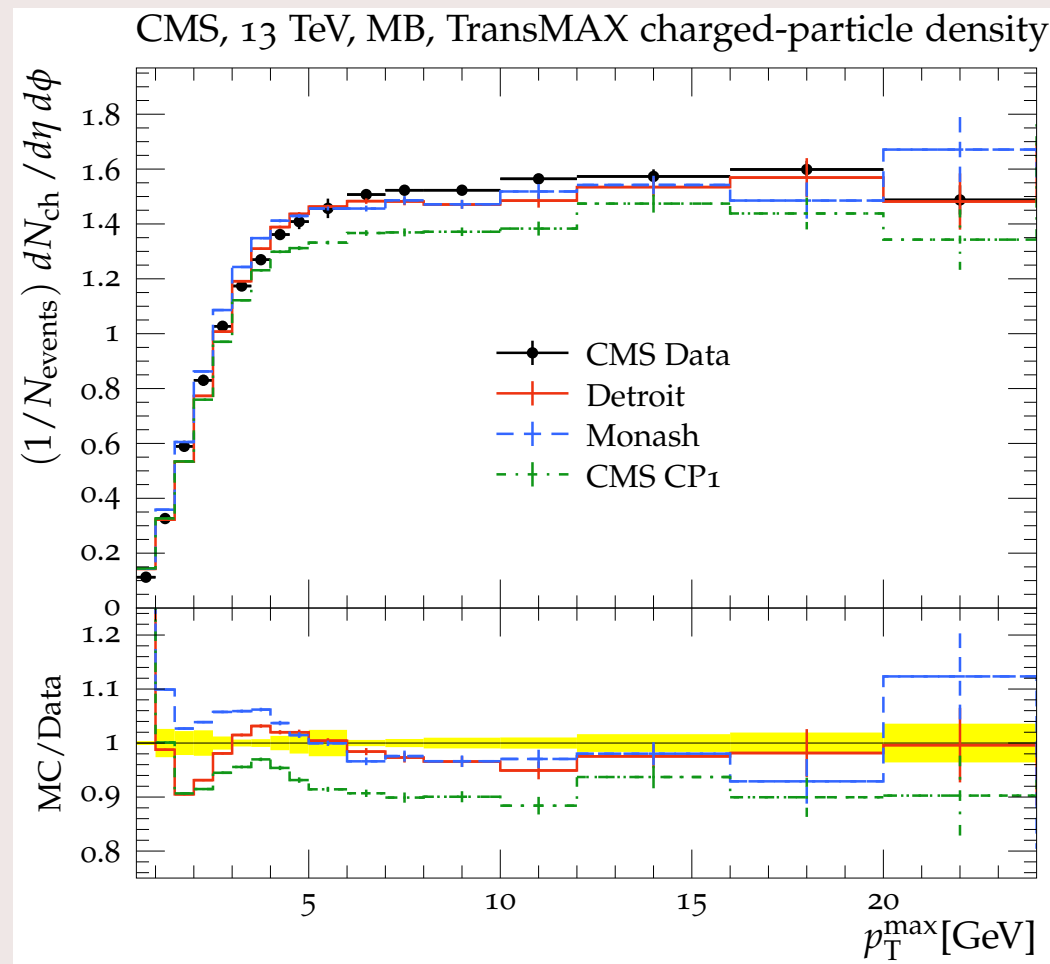


Monash tune gives best description of UE data for low p_T
 For higher p_T , **Detroit** is consistent with data
CMS CP1 underpredicts the data for all p_T

Comparison to data

LHC – 13 TeV

[CMS-PAS-FSQ-15-007](#)



At high- p_T^{max} , **Detroit** performs better than or equal to **Monash**
 At low- p_T^{max} , **Detroit** shape varies more due to proton shape function used
CMS CP1 still underpredicts the data significantly

Summary

Tuning at low energies where UE effects are relatively more important, and then extrapolating to high energies seems to work better than the reverse!

Detroit tune:

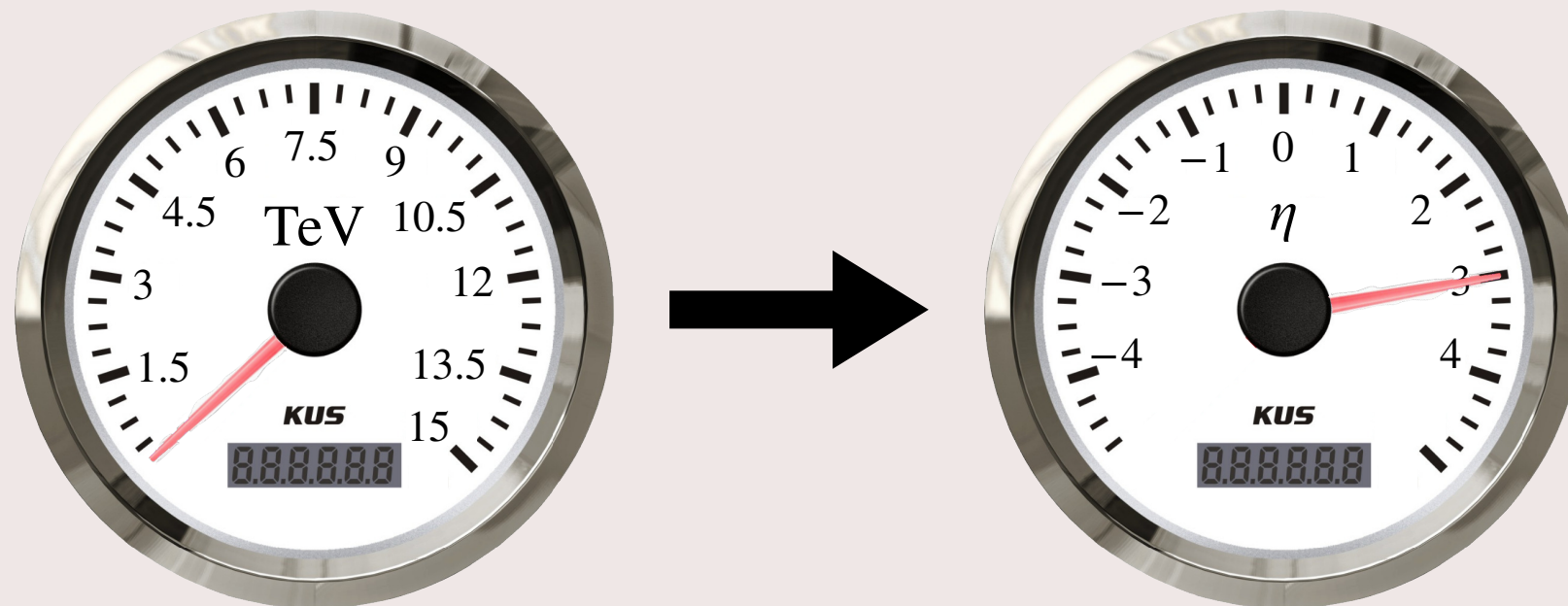
<https://github.com/mjk655/DetroitTuneOnRCF>

adjusted *MPI/UE* parameters + updated *PDFs*

→ **improved agreement**, compared to **Monash**, with RHIC + Tevatron data (UE, jet substructure, etc.) at mid-rapidity

Predictions for some LHC data are better than **CMS CP1** and at least as good as **Monash** at higher- p_T

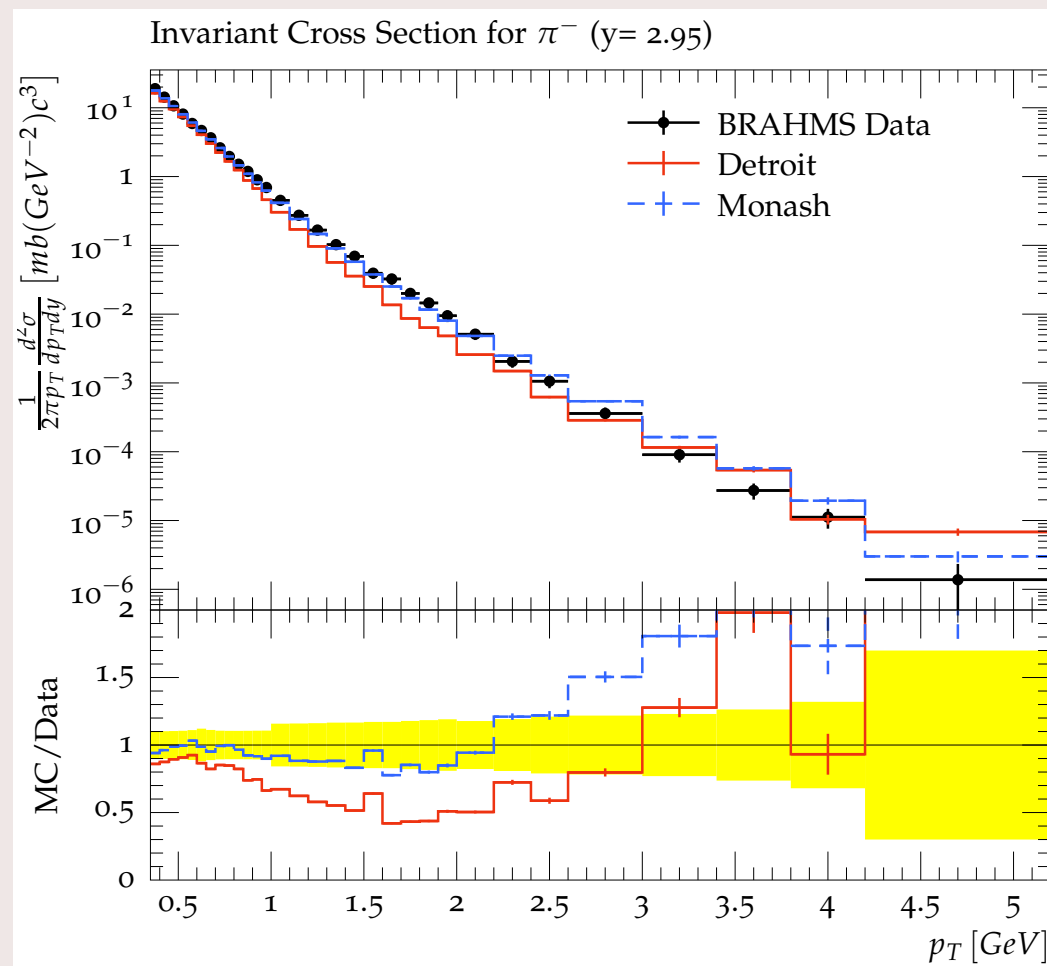
Performance at large rapidity



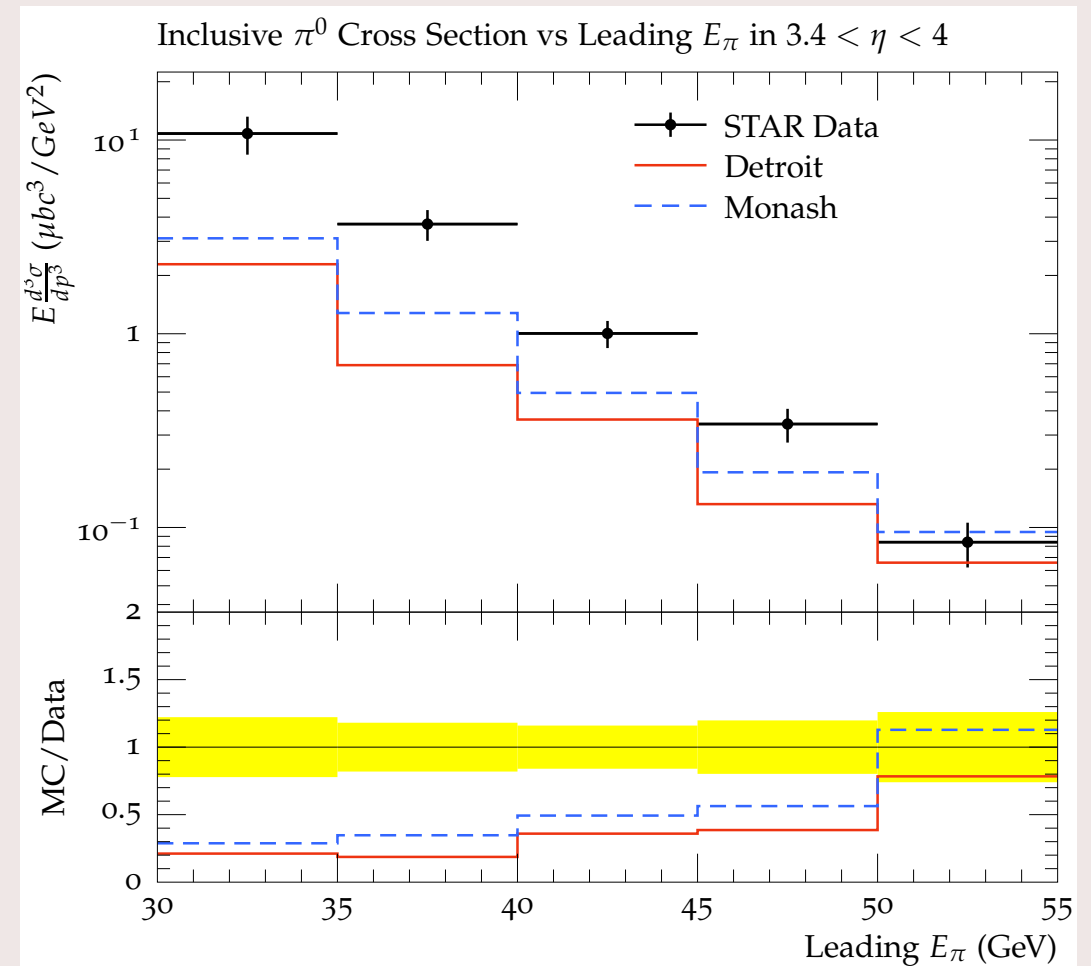
Comparison to data

Forward rapidity (200 GeV)

BRAHMS, [PRL 98 \(2007\) 252001](#)



STAR, [PRL 92 \(2004\) 171801](#)



Detroit underpredicts BRAHMS and STAR pion yields at large rapidities
Better agreement from **Monash** at low- p_T

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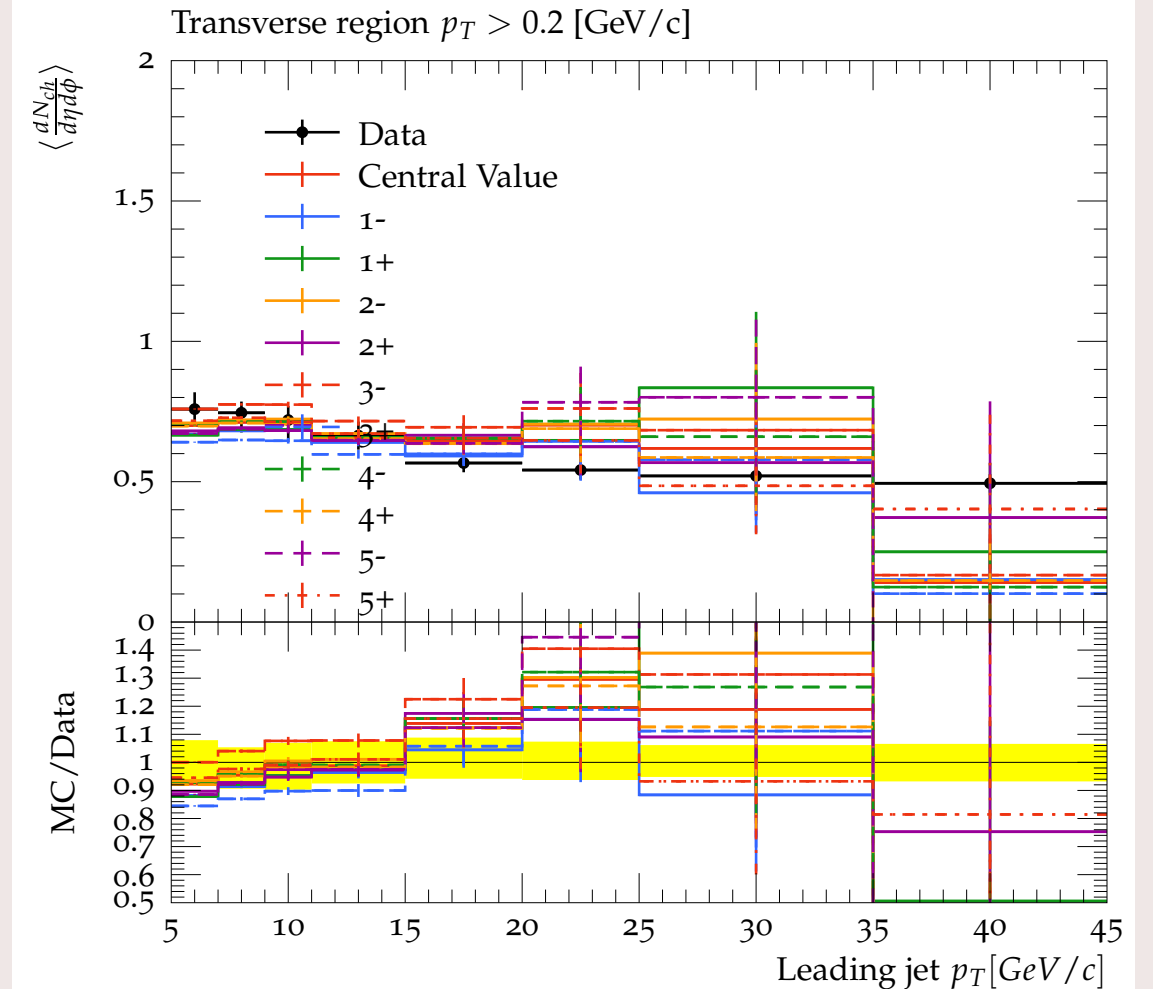
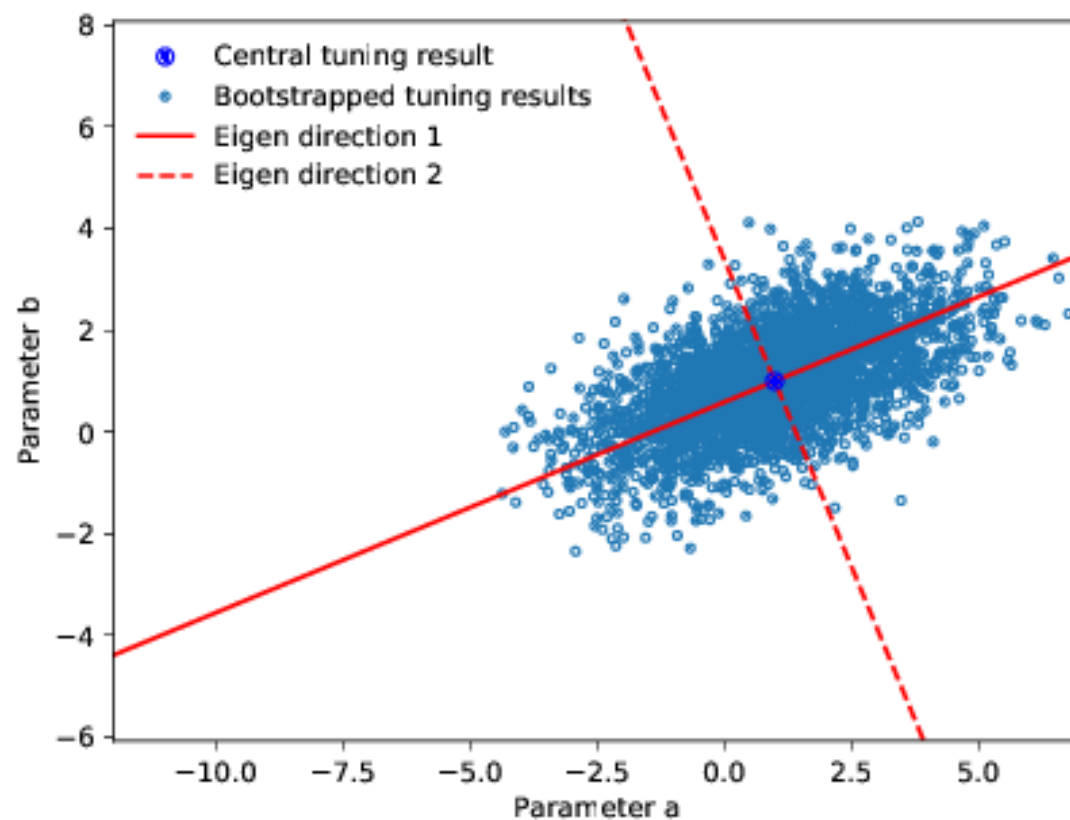
But for the future, it will be important to simultaneously describe forward and mid-rapidity RHIC data (STAR 2022 forward upgrade; EIC), which is currently not possible!

Backup

Eigentunes

STAR, [PRD 101 \(2020\) 5, 052004](#)

[PROFESSOR](#)

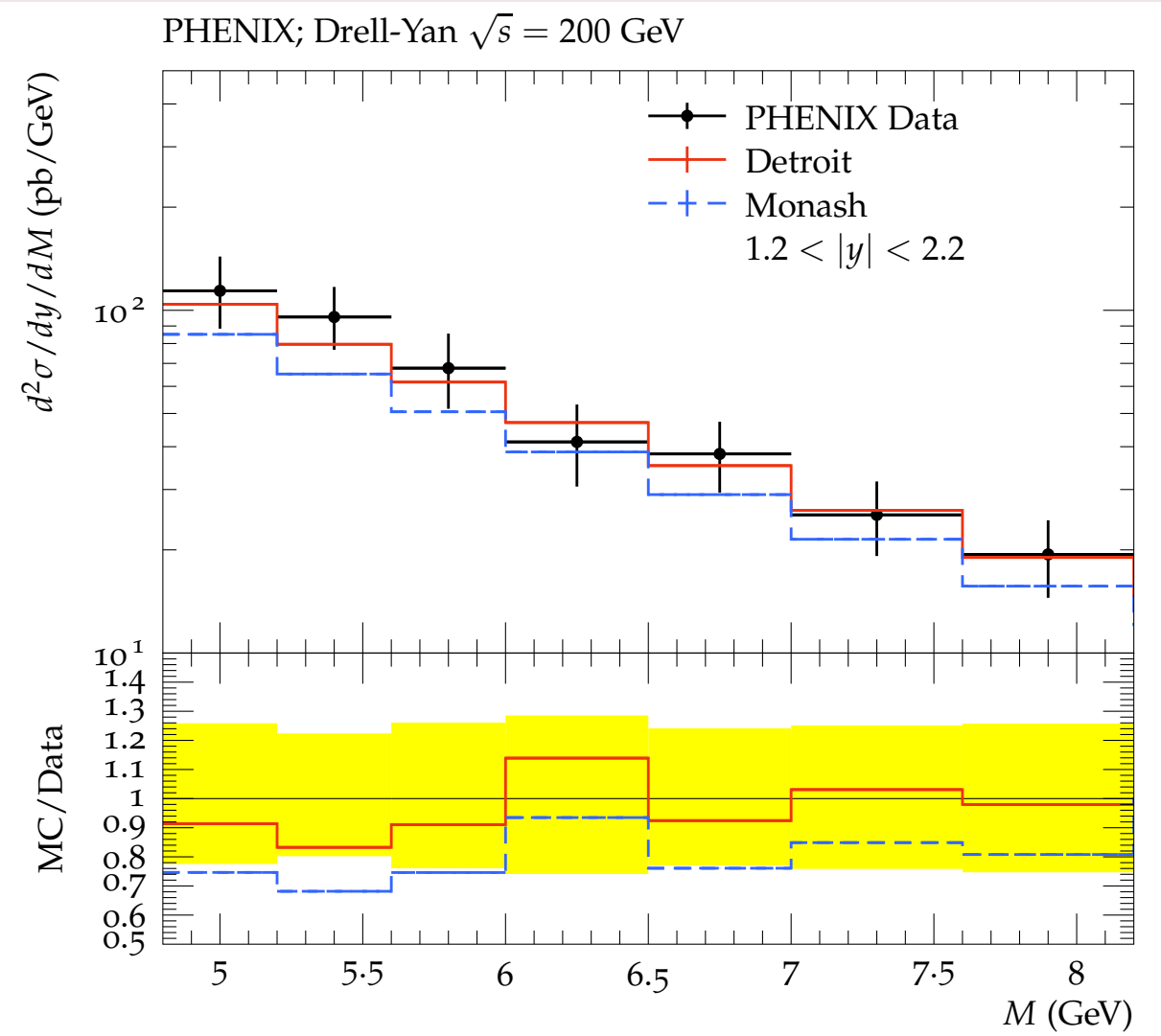
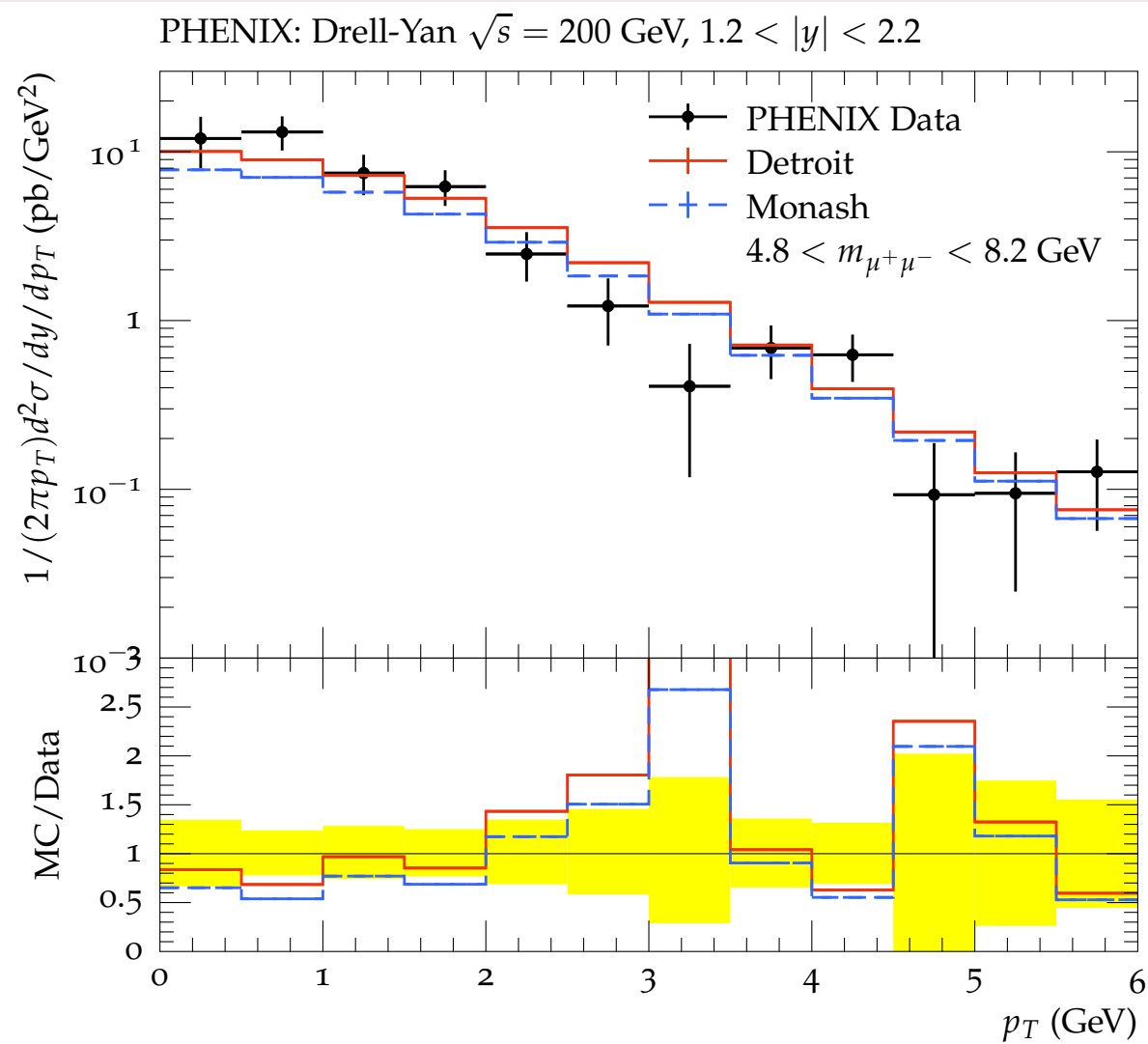


Systematic uncertainties given by reasonable variation of parameters around central value after covariance matrix diagonalization

Drell-Yan

RHIC — 200 GeV

PHENIX, [PRD 99 \(2019\) 7, 072003](#)

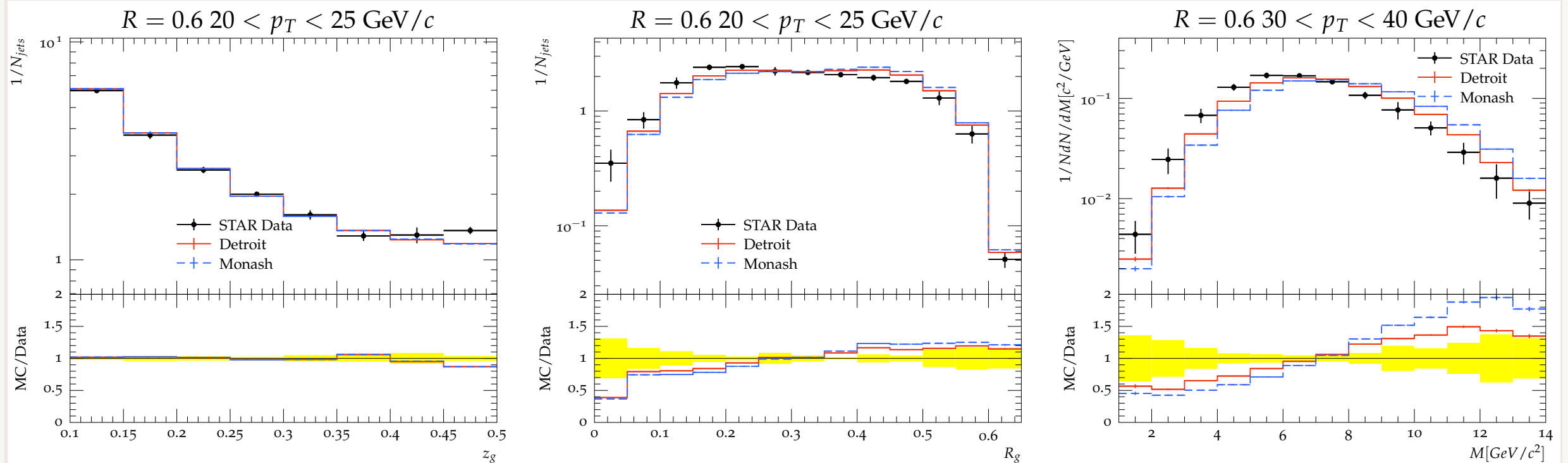


Inclusive jets

RHIC – 200 GeV

STAR, [PLB 811 \(2020\) 135846](#)

STAR, [PRD 104 \(2021\) 5, 052007](#)

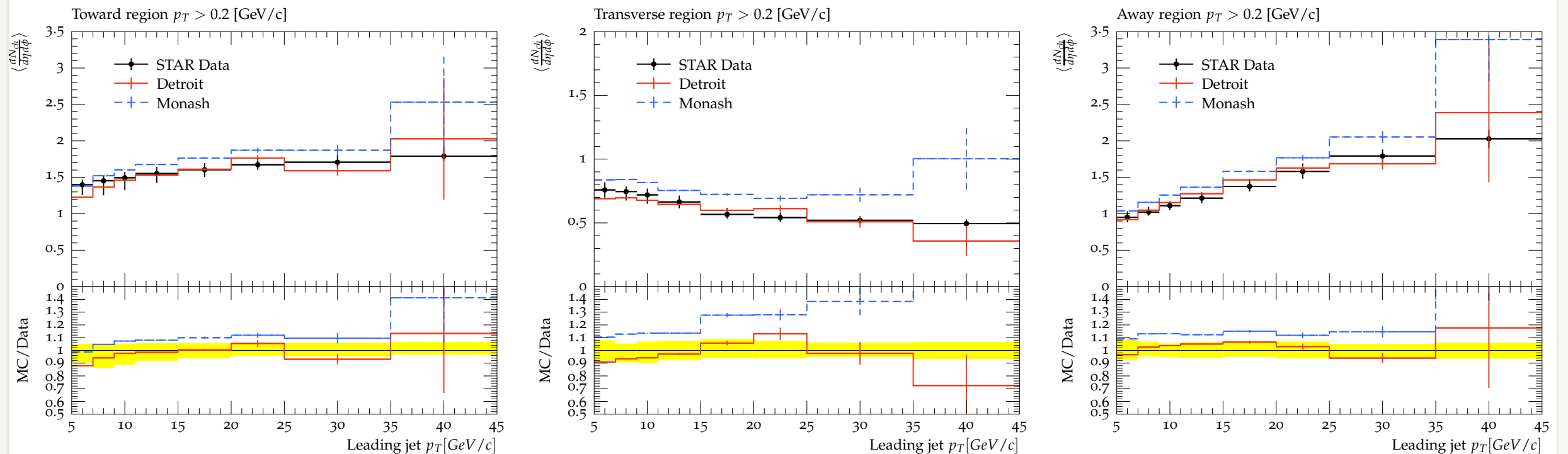


Even some high- p_T jet observables are improved by the tune.
In one case, R_g , this is even true after SoftDrop grooms away soft radiation.

STAR underlying event continued

RHIC — 200 GeV

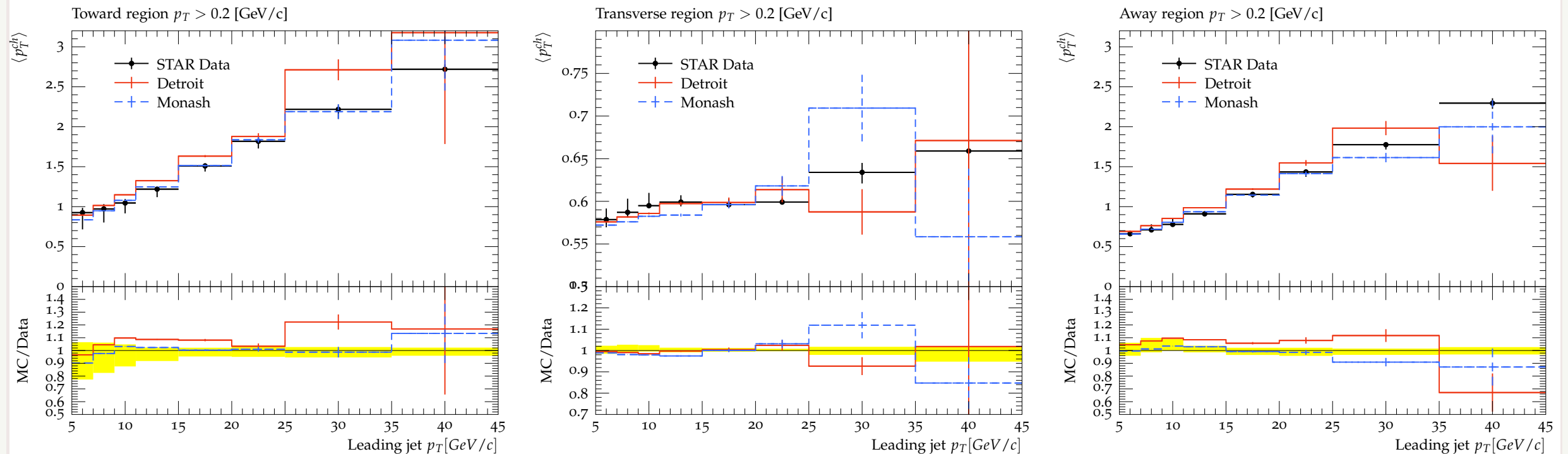
STAR, [PRD 101 \(2020\) 5, 052004](#)



STAR underlying event continued

RHIC — 200 GeV

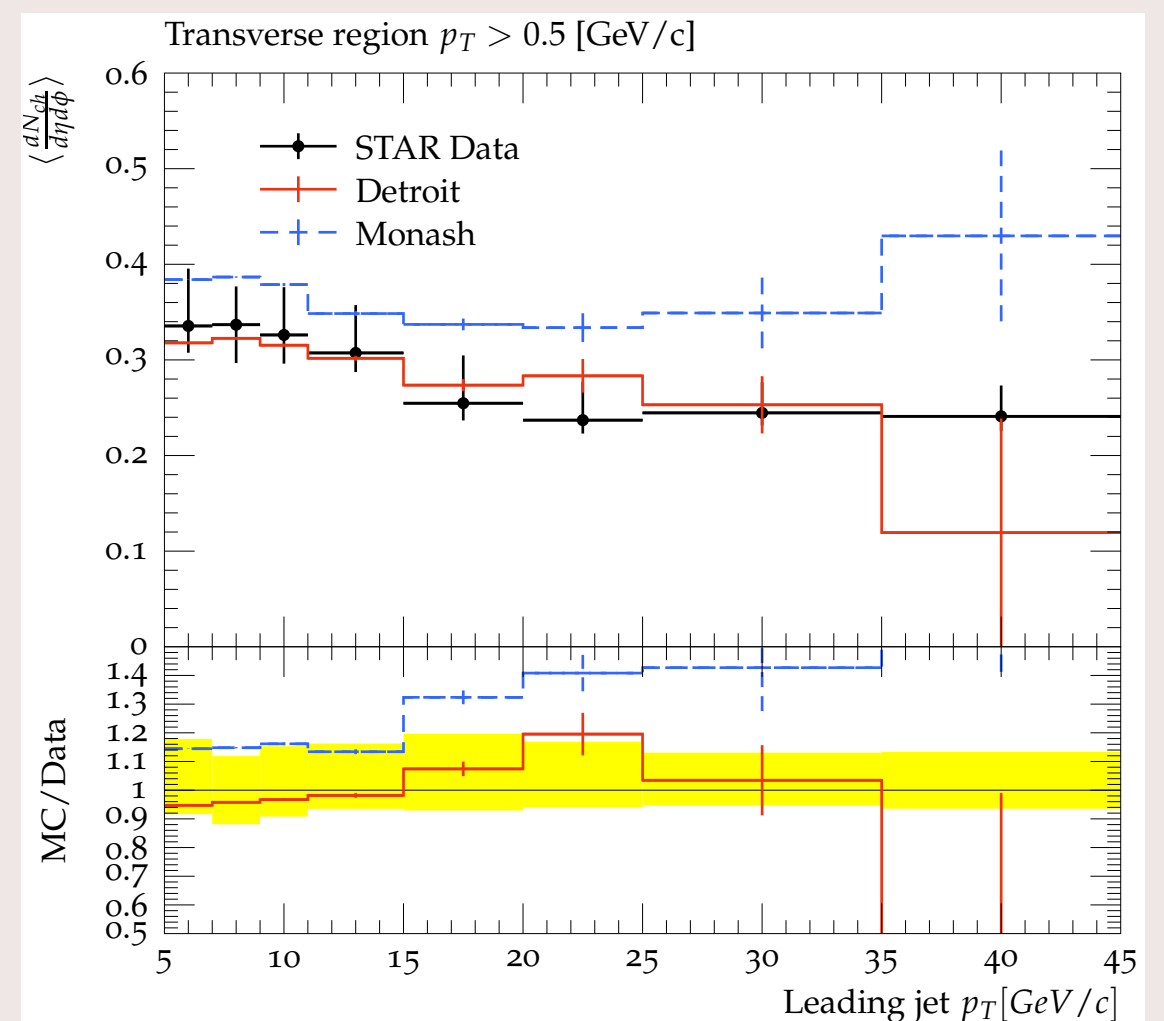
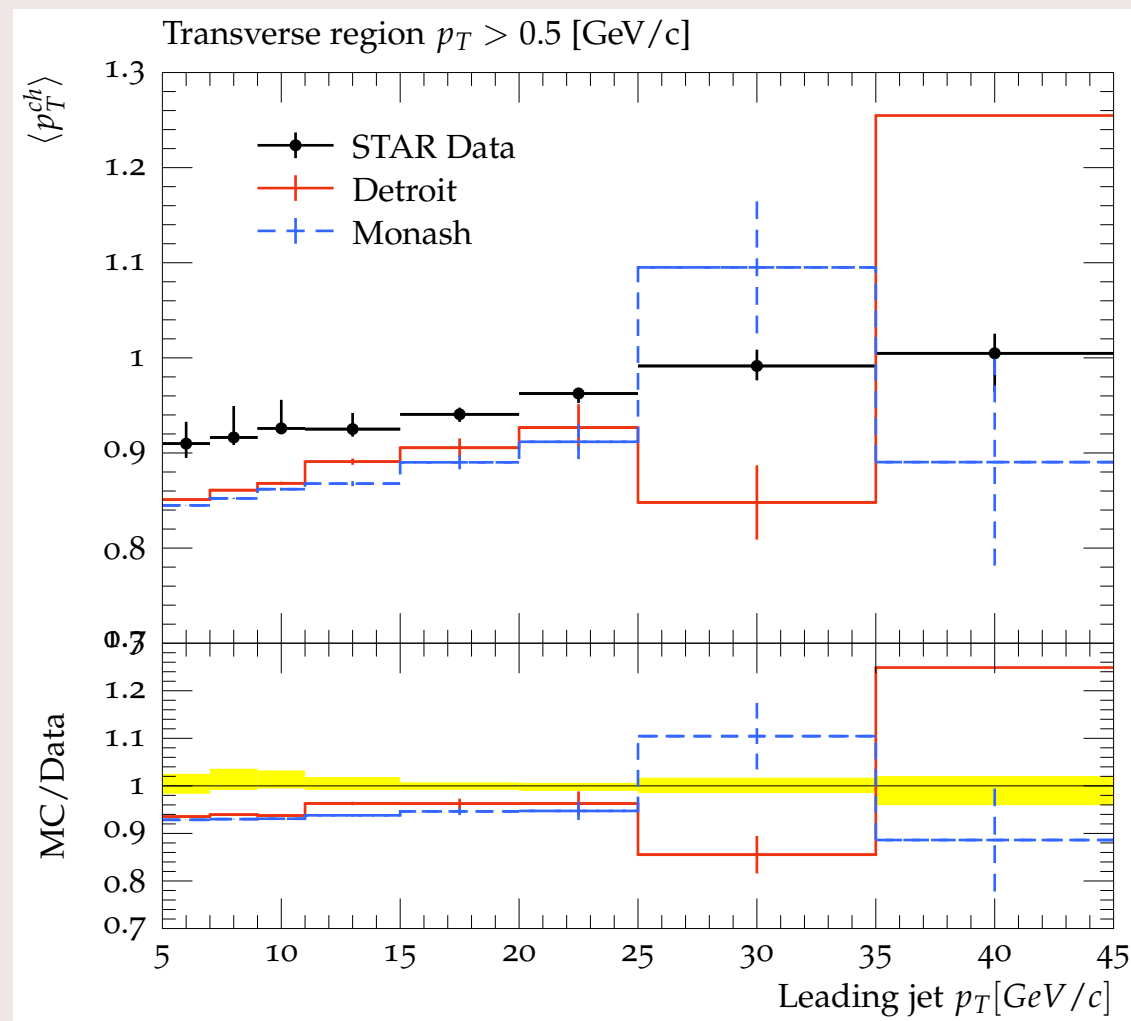
STAR, [PRD 101 \(2020\) 5, 052004](#)



STAR underlying event continued

RHIC — 200 GeV

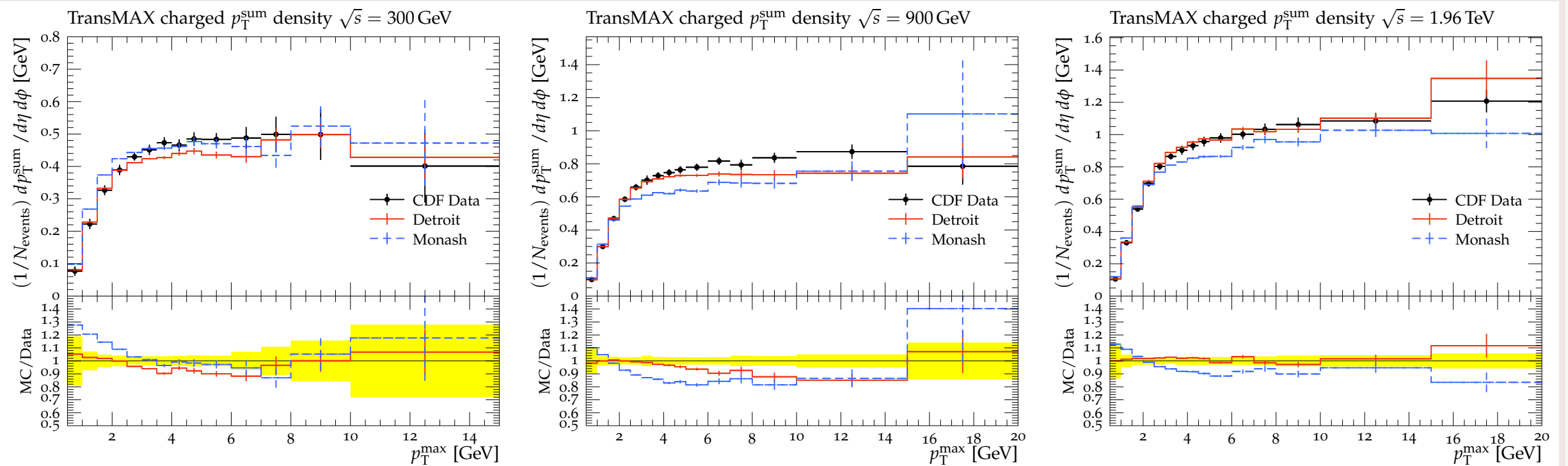
STAR, [PRD 101 \(2020\) 5, 052004](#)



CDF continued

Tevatron — 0.3 to 1.96 TeV

CDF, [PRD 92 \(2015\) 9, 092009](#)

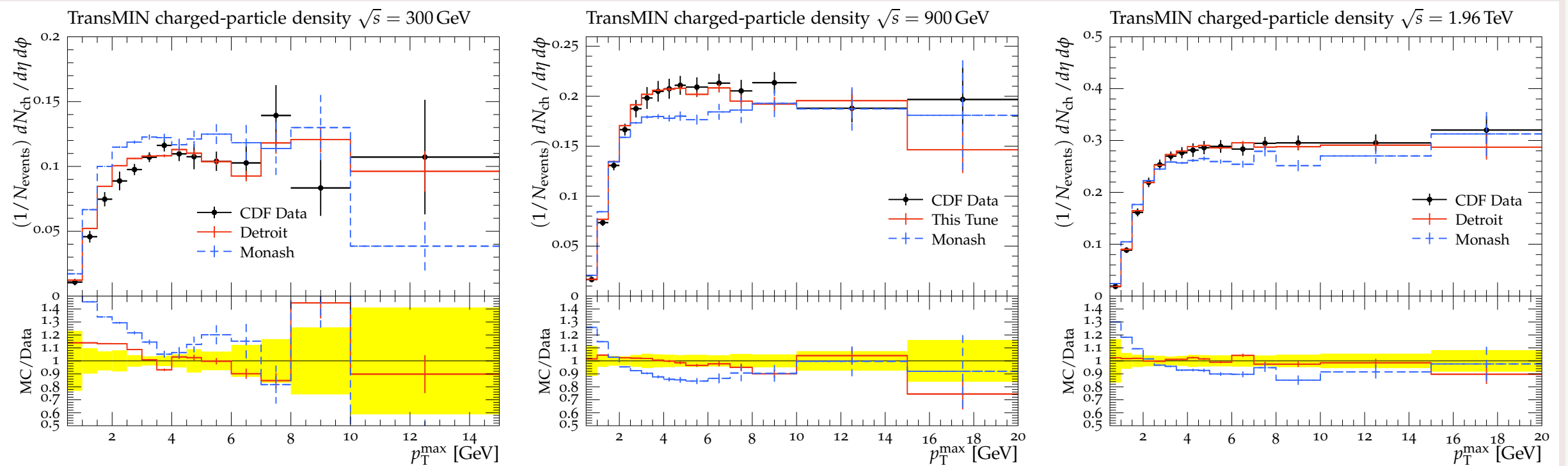


TransMAX region is less sensitive to MPI implementation

CDF continued

Tevatron — 0.3 to 1.96 TeV

CDF, [PRD 92 \(2015\) 9, 092009](#)

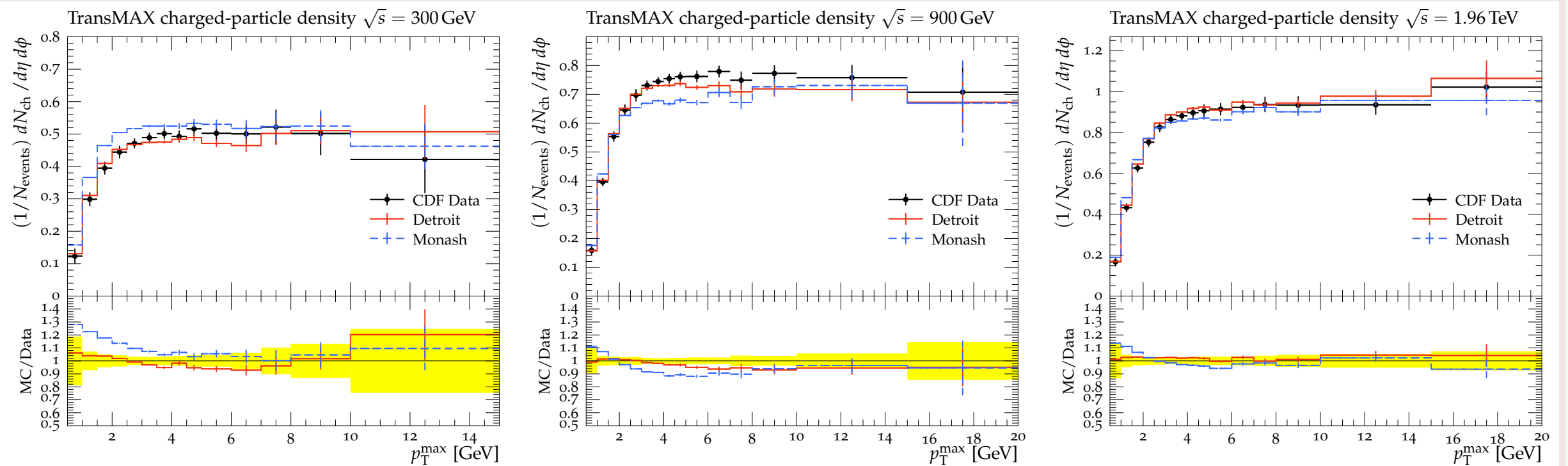


Similar behavior, and improvement by Detroit tune, to the p_T^{sum} observable

CDF continued

Tevatron — 0.3 to 1.96 TeV

CDF, [PRD 92 \(2015\) 9, 092009](#)

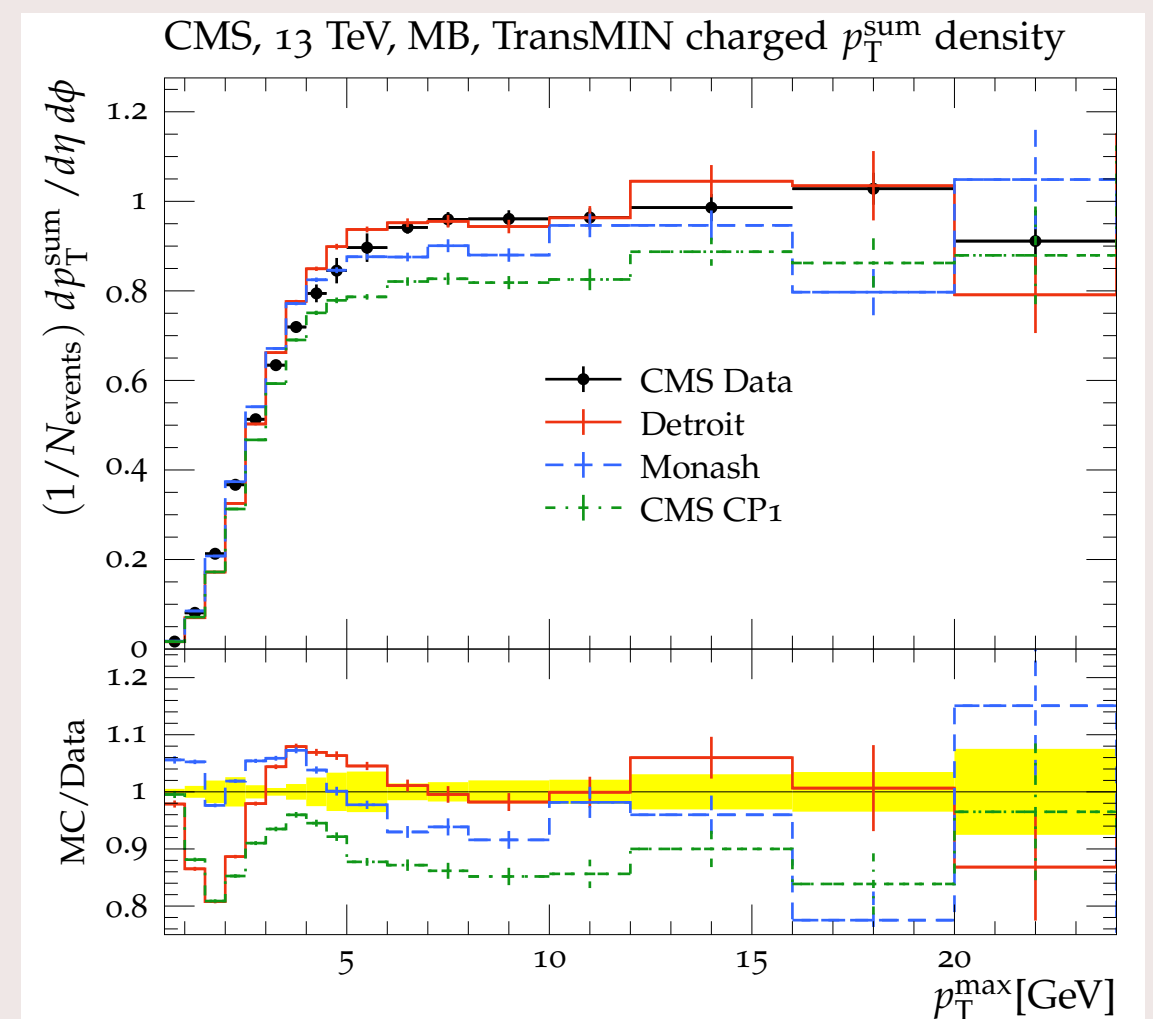
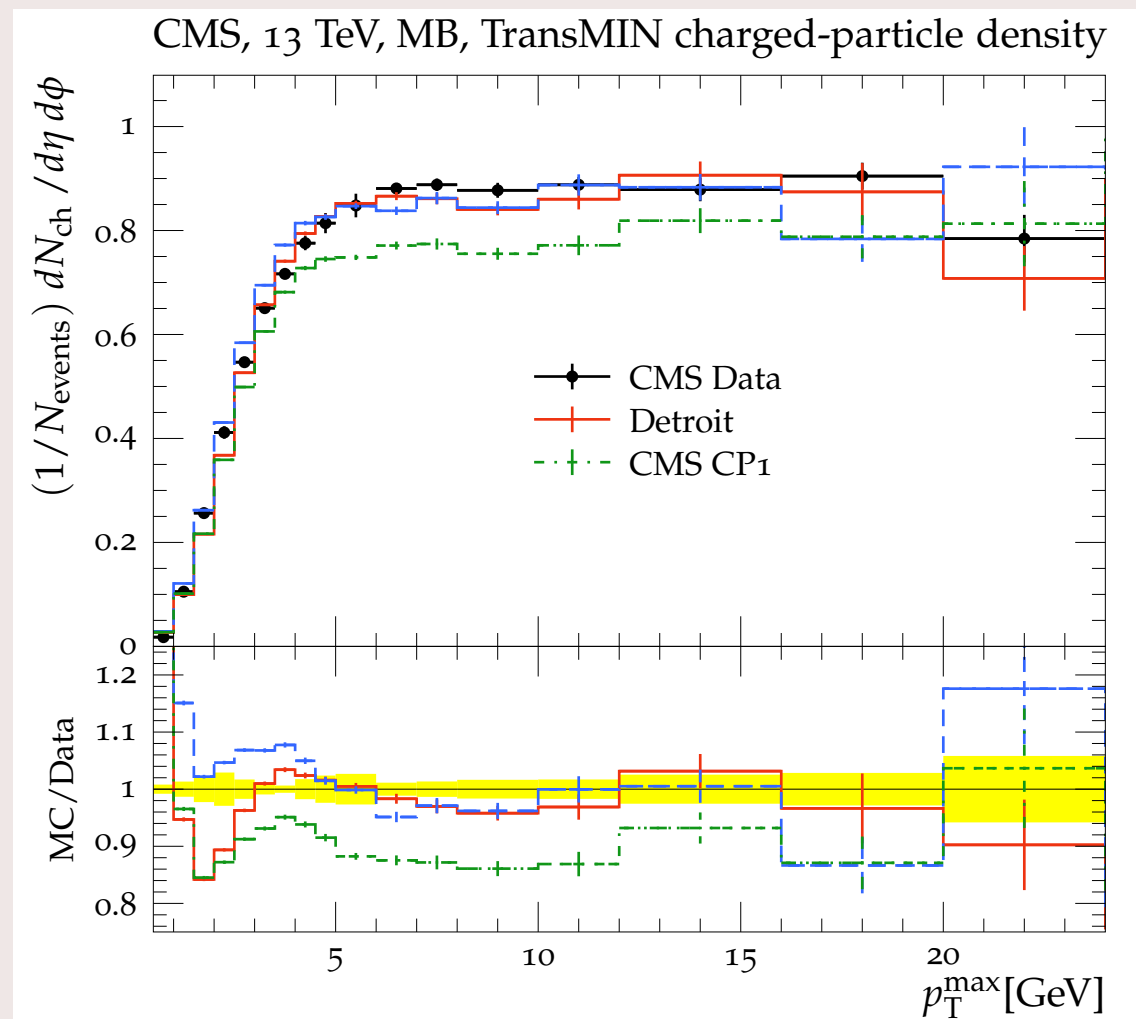


For both tunes in the TransMAX region, agreement with data is better for particle density than for p_T^{sum} , although Detroit still outperforms Monash

CMS continued

LHC – 13 TeV

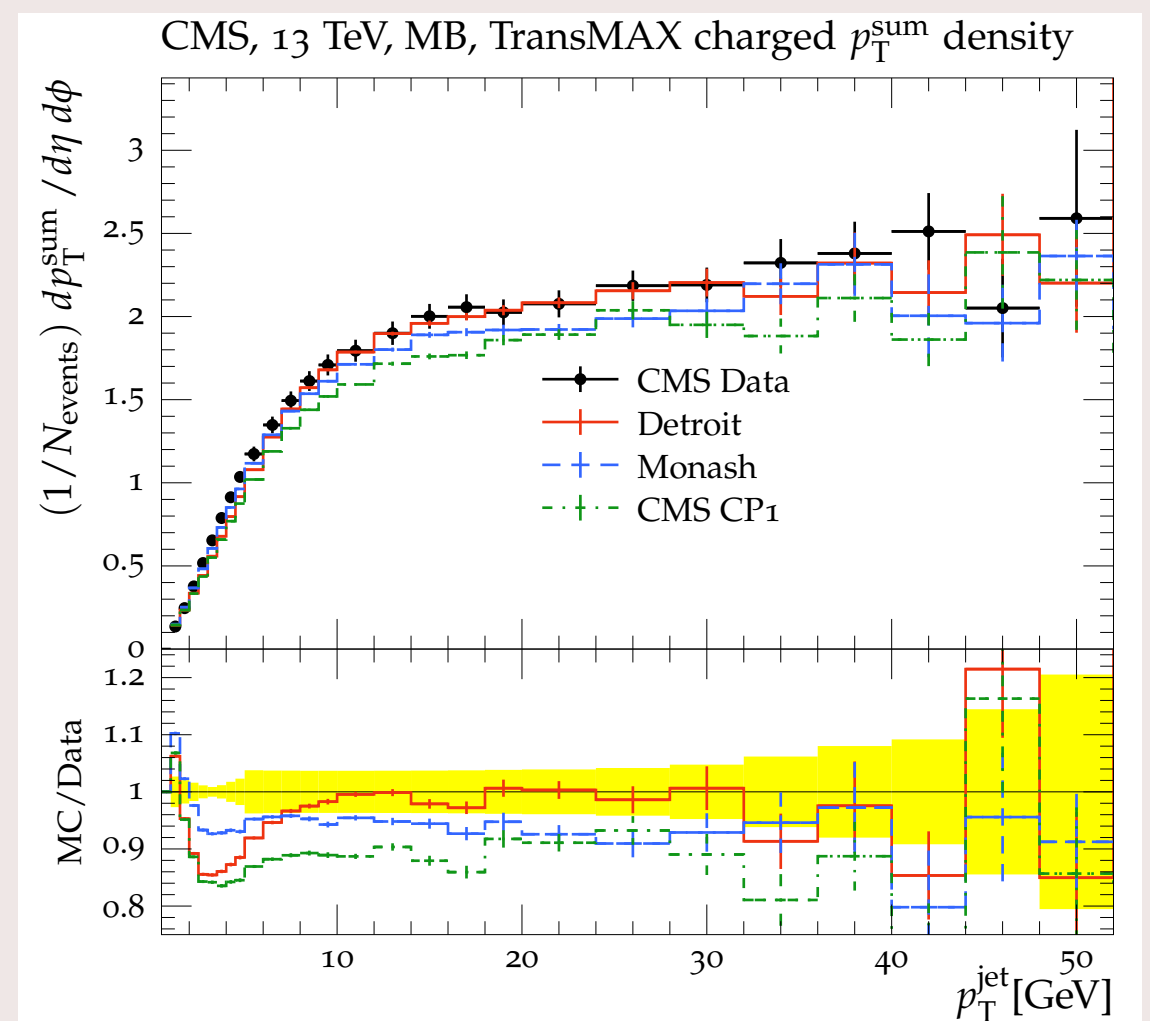
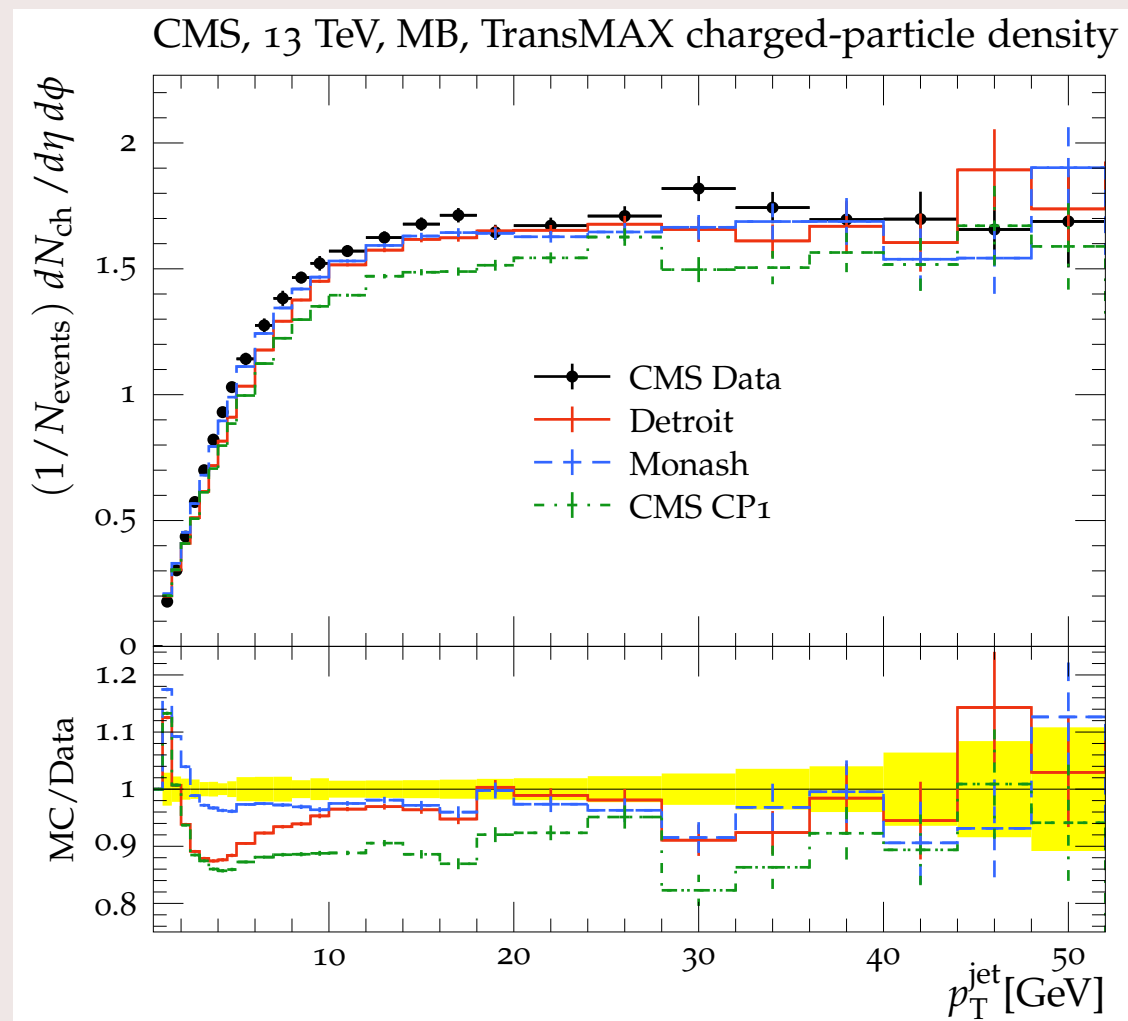
[CMS-PAS-FSQ-15-007](#)



CMS continued

LHC – 13 TeV

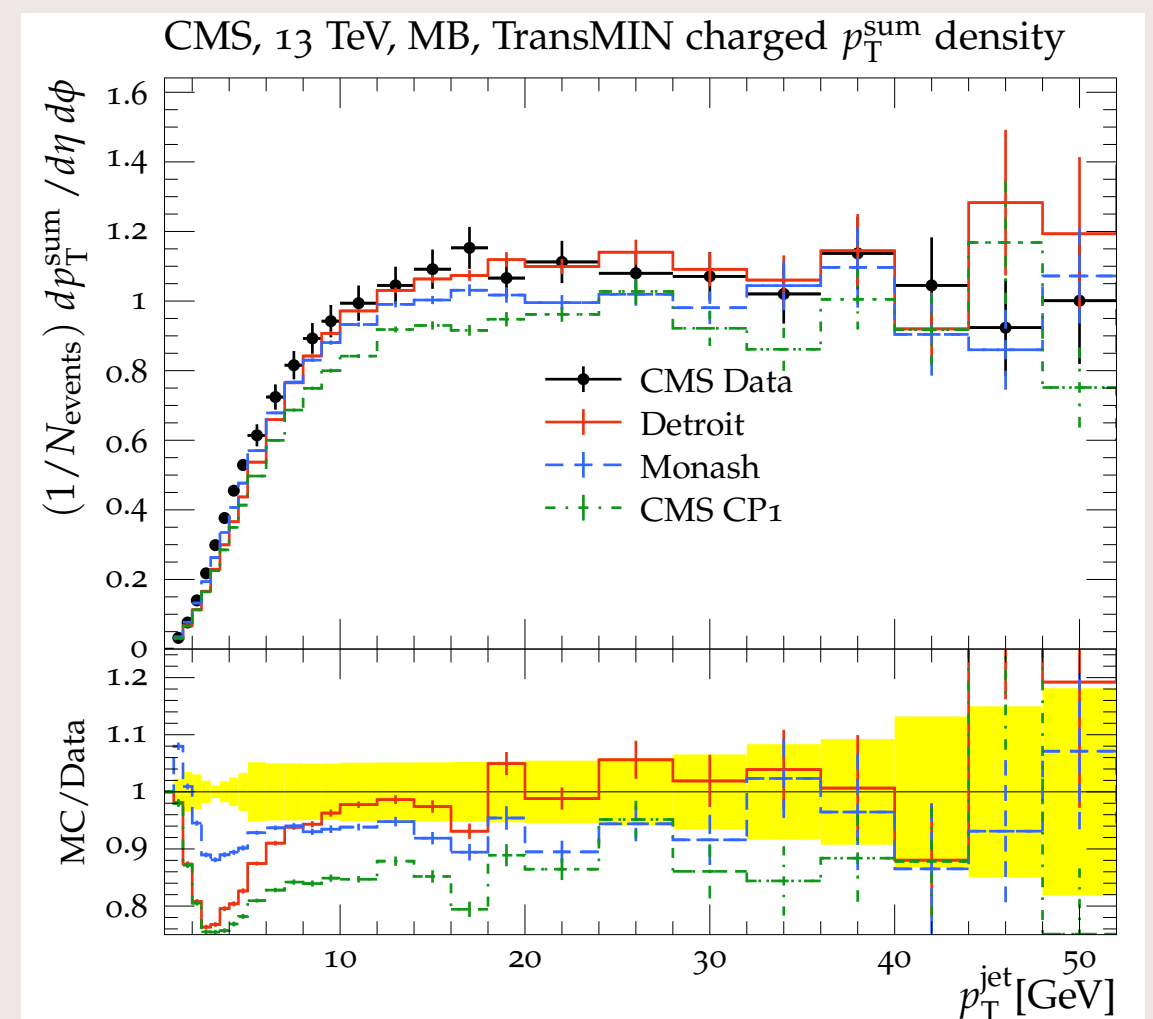
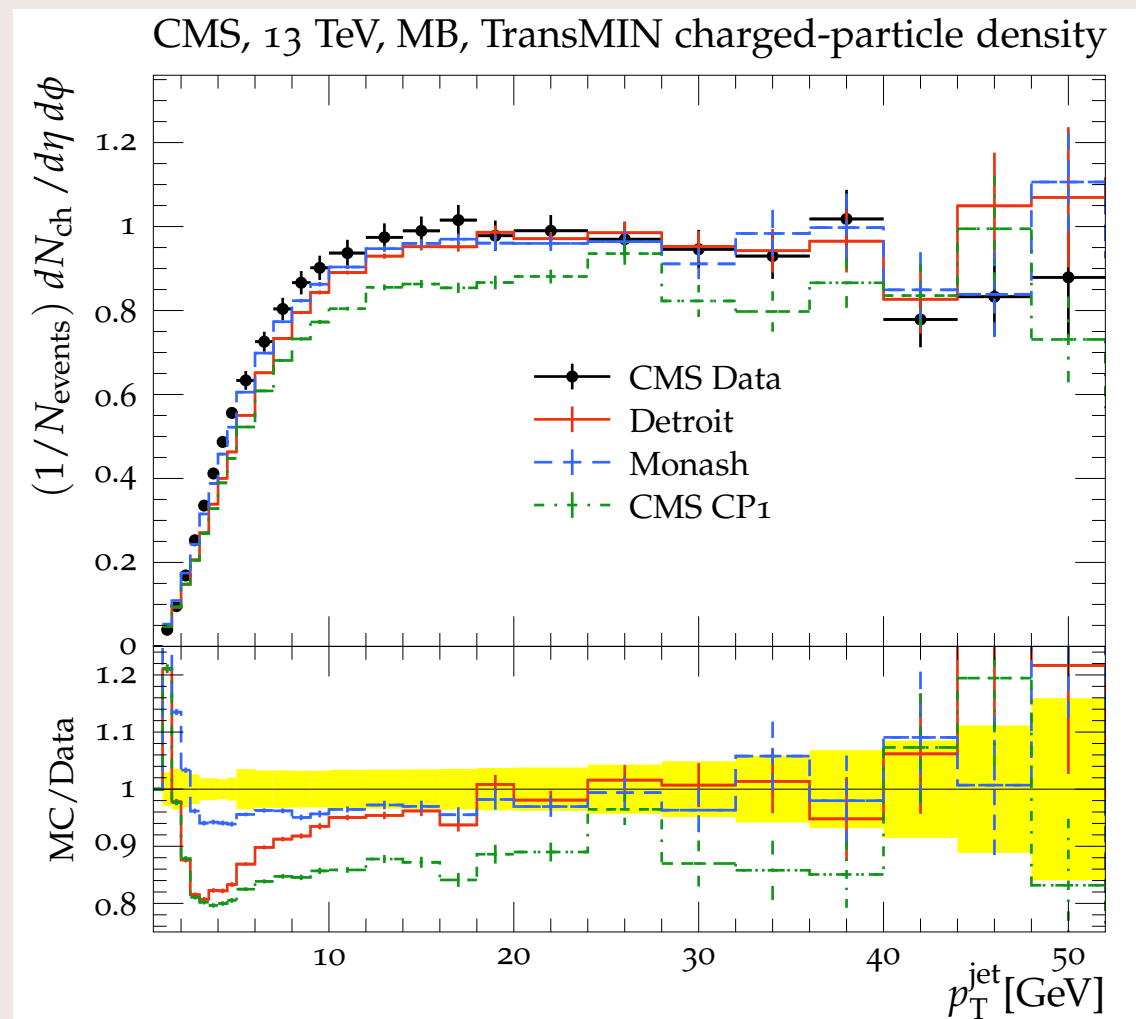
[CMS-PAS-FSQ-15-007](#)



CMS continued

LHC – 13 TeV

[CMS-PAS-FSQ-15-007](#)



Again, TransMIN region is more sensitive to MPI implementation