STAR measurements sensitive to hadronization and underlying event/multiple parton interactions

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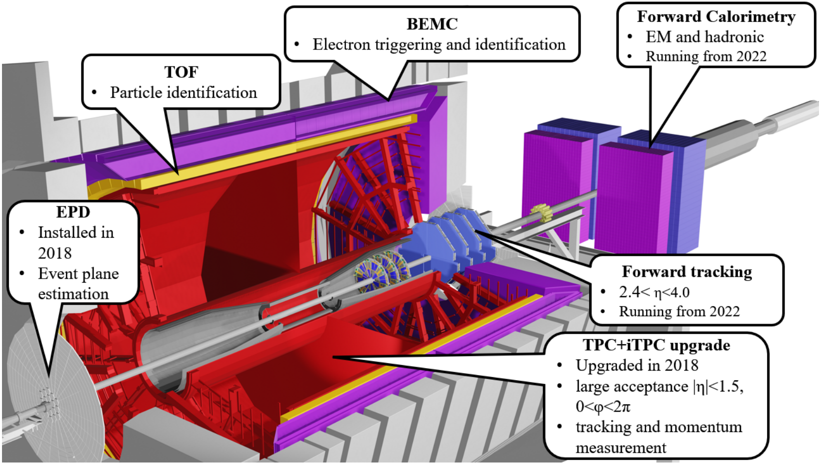
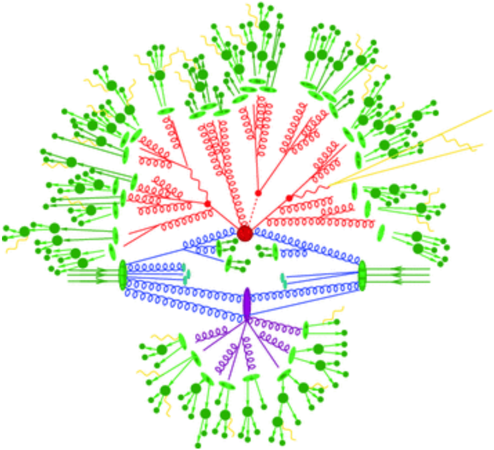


- STAR is a well suited machine for high multiplicity studies thanks to its large TPC

Soft vs. hard production mechanisms

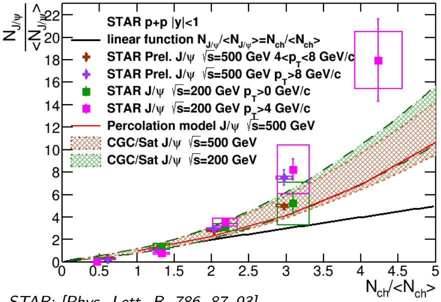
Studied with quarkonium production vs. multiplicity

- What is the collision energy dependence?
- How the scale of the hard process (p_T, m) affects the production?

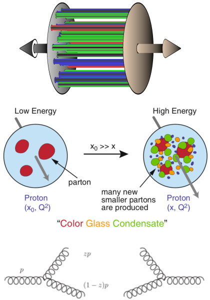


J/ψ $\sqrt{s} = 200$ GeV vs. $\sqrt{s} = 500$ GeV production vs. event activity

p+p $\sqrt{s} = 200, 500$ GeV 2012, 2011 datasets, $J/\psi \to e^+e^-$

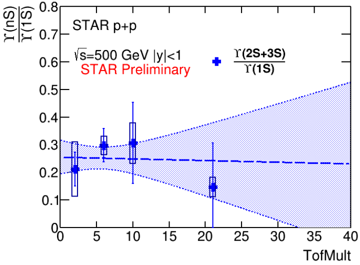


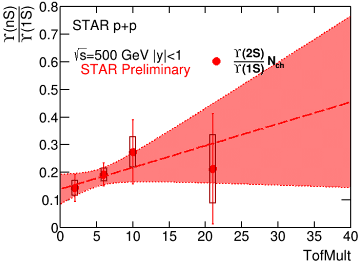
STAR: [Phys. Lett. B, 786, 87–93]



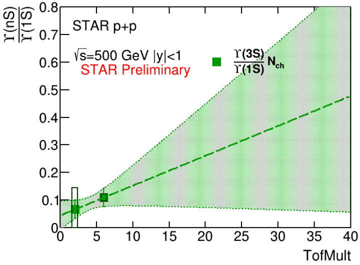
- Strong increase of J/ψ production with N_{ch}, a measure of "event activity"
- Percolation model: *[E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]*
  - Low-p_T data are well described
  - High-p_T data are above the model at high N_{ch}. Note that the calculation is for $p_T > 0$ GeV/c
- CGC/Saturation model: *[E. Levin et al., EPJC 97(5), 376(2019)], [E. Levin et al., EPJC 80(6), 560(2020)]*
  - Describes the data, however uncertainties are large
  - Data are slightly above the model at high p_T. Note that the calculation is for $p_T > 0$ GeV/c
- Possible effects of parton saturation

p+p $\sqrt{s} = 500$ GeV 2011 dataset, $\Upsilon \rightarrow e^+e^-$



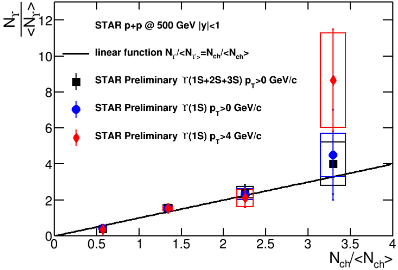


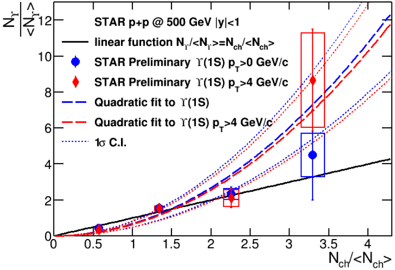
[W. Zha, et al, Phys.Rev.C 88,067901(2013)]



- Ratios vs. TofMult - no strong multiplicity dependence observed.
- TofMult: number of tracks matched to TOF within $|\eta| < 1$, $p_T > 0.2\ \mathrm{GeV/c}$ (uncorrected)
- Linear fits (solid line) and 1σ uncertainty (dashed line)

p+p $\sqrt{s} = 500\,\mathrm{GeV}$ 2011 dataset, $\Upsilon \to e^+e^-$

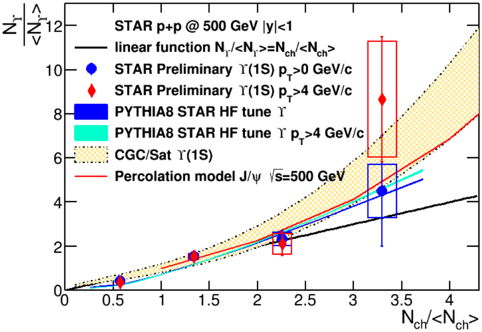




- Self-normalized yield vs. self-normalized multiplicity in p+p $\sqrt{s} = 500\,\mathrm{GeV}$ measured for $\Upsilon(1S+2S+3S)$ and $\Upsilon(1S)$
- Data consistent with a linear rise (black line), with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4\,\mathrm{GeV/c}$
- Percolation model predicts quadratic dependence $\frac{N_{hard}}{\langle N_{hard}\rangle} = \langle\rho\rangle \left(\frac{\frac{dN_{ch}}{d\eta}}{\left\langle\frac{dN_{ch}}{d\eta}\right\rangle}\right)^2$ at high multiplicity [E. G. Ferreiro, C. Pajares, Phys.Rev. C, 86, 034903 (2012)]
- Quadratic fit $y = ax^2$ describes the data, suggest quenching due to overlapping strings

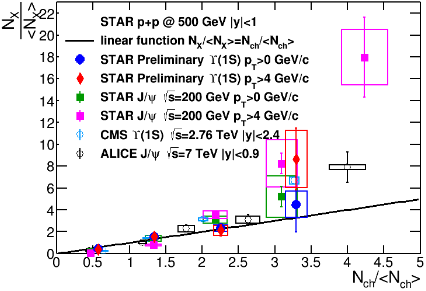
Υ production vs. event activity - models

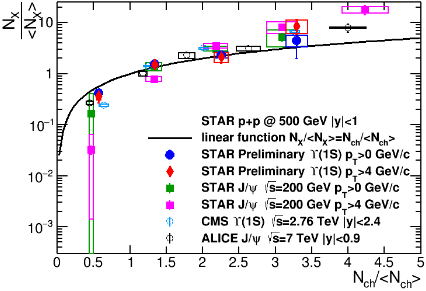
p+p $\sqrt{s} = 500\,\mathrm{GeV}$ 2011 dataset, $\Upsilon \to e^+e^-$



- PYTHIA8 and Percolation models reproduce the trend in the data
  [E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]
  - MPI or string quenching effects
- CGC/Saturation model describes the data within large uncertainties
  [E. Levin M. Siddikov, EPJC, 97(5), 376(2019)], [EPJC 80(6), 560(2020)]
  - Hint of saturation effects

p+p $\sqrt{s} = 500\ \mathrm{GeV}$ 2011 dataset, $\Upsilon \rightarrow e^{+}e^{-}$



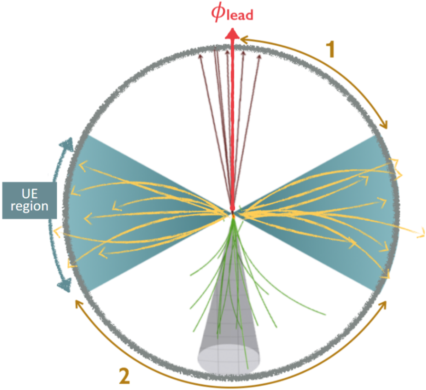


[JHEP04,103(2014)], [Phys.Lett.B 712,165–175(2012)], STAR [Phys.Lett.B 786,87-93(2018)]

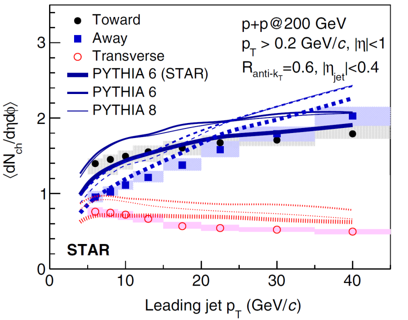
- Similar trend at RHIC and LHC for Υ and J/ψ
  - Seems to be independent of mass or collision energy

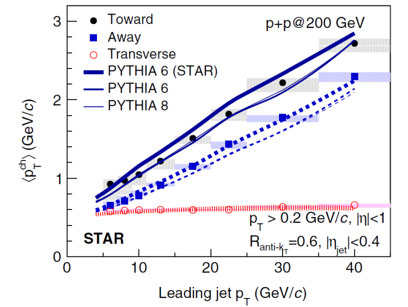
Effect of jets on underlying event

- Study jets and correlations vs. underlying event
- Underlying event can be studied in the transverse direction relative to jet



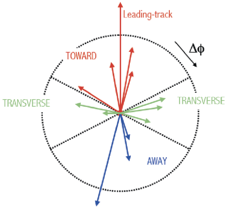
[V. Verkest, DNP 2022]



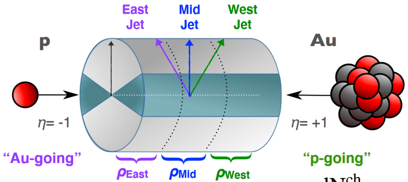


STAR: [Phys. Rev. D 101, 052004]

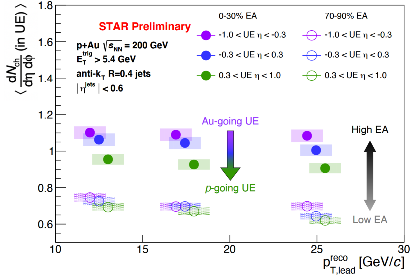
- Studies of UE in jets in 3 regions:
  - toward, away, transverse
- The $< \frac{dN_{ch}}{d\eta d\phi} >$ increases with leading jet p_T in the toward and away directions
- Strong dependence of $< p_T >$ on leading jet p_T in the toward and away directions
- Weak dependence of $< \frac{dN_{ch}}{d\eta d\phi} >$ and $< p_T >$ in the transverse direction
- Hint of small contributions to UE from initial (ISR) and final state radiation (FSR)



[J. Fiete G-O, Joliot-Curie International School 2018]

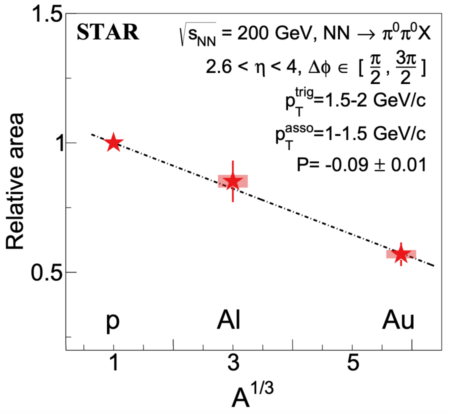


$$\rho = \frac{dN^{ch}}{d\eta d\phi}$$



- Underlying event UE is defined as charged particles within $1 < |\phi_{lead} - \phi_{UE}| < \pi - 1$
- Higher UE N_{ch} in events with large event activity measured by the BBC in *Au*-going direction
- Larger UE in the *Au*-going direction
  - No significant dependence on leading jet p_T

Evidence of non-linear gluon dynamics



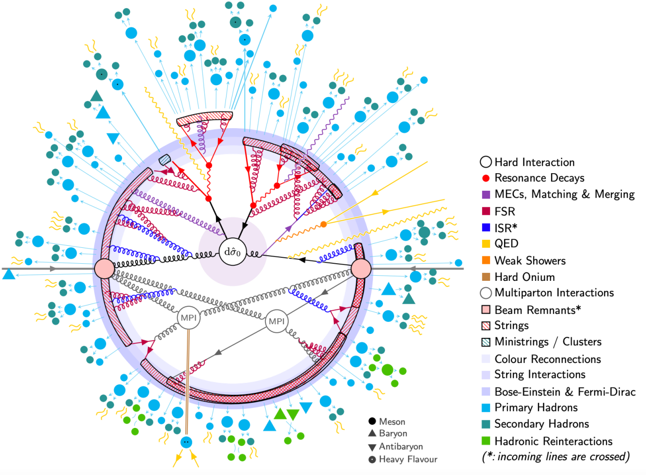
STAR: [Phys. Rev. Lett. 129, 092501]

- Opportunity to test CGC with jets
- Back-to-back azimuthal correlations of di-π_0 at forward pseudorapidity $(2.6 < \eta < 4.0)$
  - measured in $p+p$, $p+Al$, and $p+Au$
- Relative area: area of away-side peak of the correlation function with respect to $p+p$
- Clear A-dependent suppression of back-to-back yields in $p+A$ compared to $p+p$ for small-x (and Q^2) pairs with low p_T

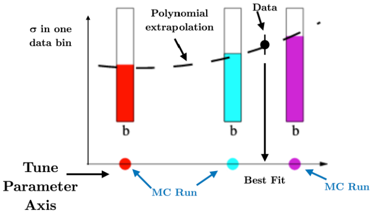
STAR Pythia8 "'Detroit"' Tune

Towards comprehensive description of $p + p$ collisions at RHIC energy (not only!)

[Aguilar et al., Phys. Rev. D 105, 016011]



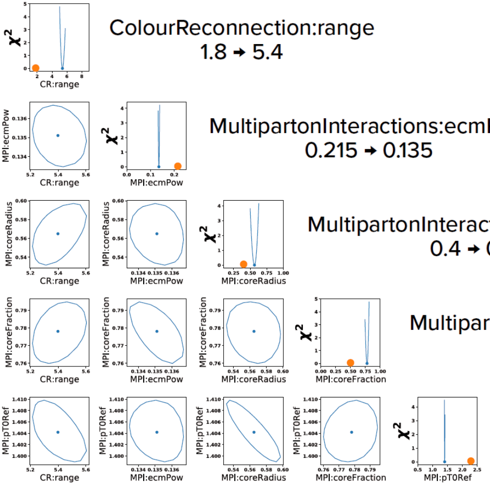
Detroit Pythia8 Tune - input data and procedure



Experiment	$\sqrt{s}$ (GeV)	Observable	Reference	Figure
STAR	200	$\pi^{\pm}$ cross sections vs p_T	[24]	3, 14
PHENIX	200	Dimuon pairs from Drell-Yan vs di-muon p_T	[25]	16
STAR	200	Average charged particle multiplicities and p_T vs leading jet p_T in the forward, transverse, and away regions	[15]	3, 8, 9
CDF	300, 900, 1960	Charge particle density and $\sum p_T$ vs leading hadron p_T in transverse region	[18]	10, 11, 12
STAR	200	SoftDrop groomed jet substructure (z_g and R_g)	[26]	15
STAR	200	Inclusive and groomed jet mass	[27]	3, 15

- Tuned using Professor tool: *[EPJC 65 (2010) 331-357]*
  - Interpolate
  - Minimize χ^2
- Used a wide data sample from STAR and Tevatron
  - Combines soft and hard processes
    - Cross sections, multiplicity distributions, jet characteristics
  - Included in Rivet

Detroit Tune - tuned parameters



ColourReconnection:range
1.8 → 5.4

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

MultipartonInteractions:ecmPow
0.215 → 0.135

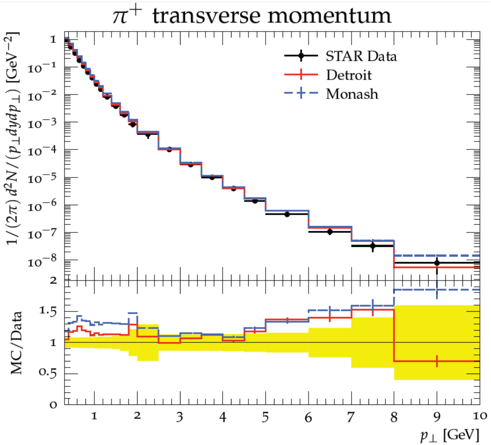
MultipartonInteractions:coreRadius
0.4 → 0.56

MultipartonInteractions:coreFraction
0.5 → 0.78

MultipartonInteractions:pT0Ref
2.28 → 1.40 GeV

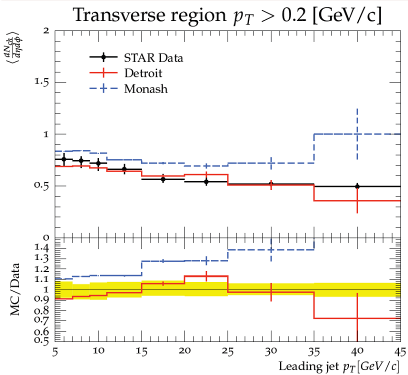
[Aguilar et al., Phys. Rev. D 105, 016011]

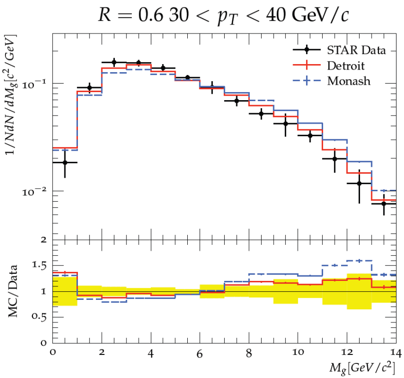
$$p_{T,0} = p_{T,0}^{ref}\left(\frac{\sqrt{s}}{\sqrt{s}_{ref}}\right)^{\mathrm{ecmPow}}$$



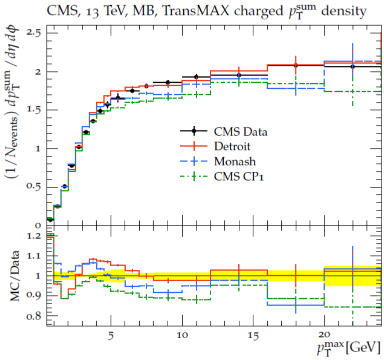
- Better description of STAR data with Detroit than Monash tune

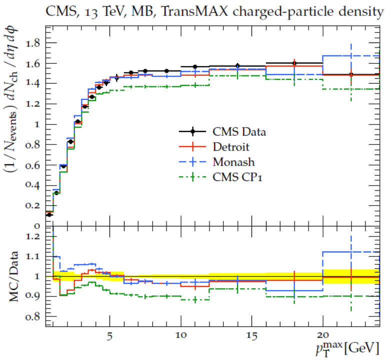
Description of RHIC data - Jets vs. UE





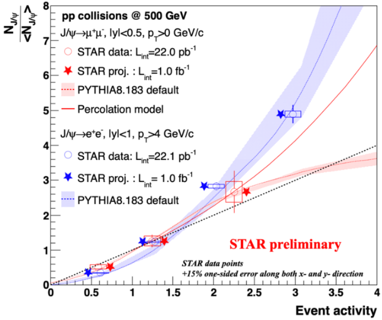
- Better description of STAR data with Detroit than Monash tune
- Simultaneous description of underling event and jet substructure

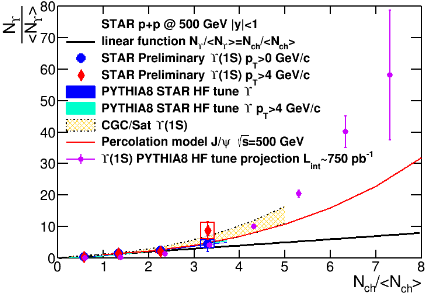




CMS-PAS-FSQ-15-007

- High p_T - better description with Detroit than Monash
- Low p_T - larger variation due to the proton shape used
- In general better performance when extrapolating from RHIC energy to LHC
  - This opens a possibility of more tuning at lower energies
  - Will be important for upcoming Electron Ion Collider

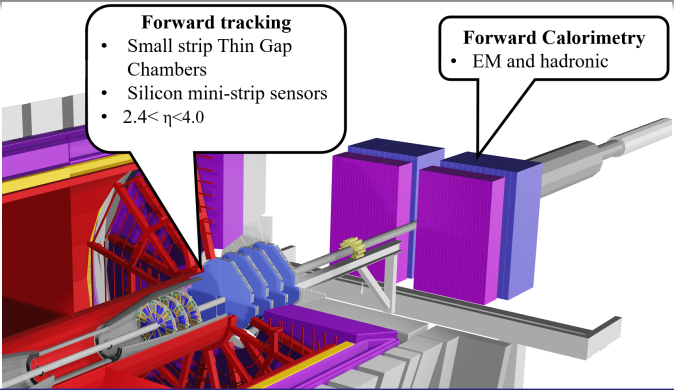




Projections 2017+2022

- High precision measurement of J/ψ and Υ dependence on normalized N_{ch}
- Very high integrated luminosity:
  - $\mathcal{L}_{int} \sim 750\,\mathrm{pb}^{-1}$ for Barrel High Tower triggered e - high energy electrons
  - $\mathcal{L}_{int} \sim 375\,\mathrm{pb}^{-1}$ for $\mu\mu$ triggers
- Possible to discriminate different models
- 2017 data is already 10x more than 2011

Prospects - Forward Upgrade



Future plans for STAR

- Forward upgrade $2.5 < y < 4$ [a] - already installed and running
  - Silicon detectors (FST) - tracking
  - Small-strip Thin Gap Chambers (sTGC) - tracking
  - Electromagnetic and hadronic calorimeters - jet energy measurements
- High integrated luminosity for precision quarkonium production studies both at mid and forward rapidity
- Collect $p+p$, $p+A$, $Au+Au$ data at $200\ \mathrm{GeV}$ for comprehensive studies

[a] https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

Summary

Multiplicity dependence of quarkonium production

- Similar trend observed for J/ψ and Υ at RHIC and LHC
  - Same effects at different energies and mass scales
- Percolation Model, PYTHIA and CGC/Sat models qualitatively describe the data
  - Indication of quarkonium production in MPI
  - Possible effect of parton saturation
- More data coming as well as opportunity to study it at forward vs. mid-rapidity

Studies of UE with jets and correlations

- UE measured in the transverse region shows very weak dependence on leading jet p_T
  - Hint of small contributions of ISR and FSR to UE
- di-π_0 correlations at forward η show indication of non-linear gluon effects

STAR Pythia8 Detroit tune

- Optimized Underlying Event and MPI parameters as well as PDFs
- Better performance than Monash tune at RHIC and Tevatoron energies
- Good performance at LHC suggests its better to extrapolate from low to high energies
  - More opportunities of tuning at low energies
  - Important for future EIC

Thank you for your attention!

BACKUP

Detroit - energy extrapolation