The PYTHIA event generator and MPI

Richard Corke

Department of Astronomy and Theoretical Physics
Lund University

December 2010

Overview

Model overview

Interleaved evolution

- Note: what follows covers the current framework of PYTHIA 8

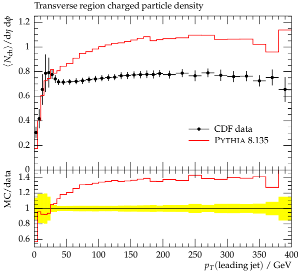
- Transverse-momentum-ordered parton showers
- MPI also ordered in $p_\perp$
  - Mix of possible underlying event processes, including jets, γ, J/ψ, DY, ...
  - Radiation from all interactions
- Interleaved evolution for ISR, FSR and MPI

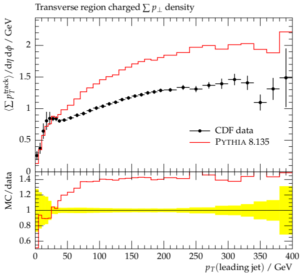
$$
\begin{aligned}
\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} &= \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \\
&\times \exp\left(- \int_{p_\perp}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)
\end{aligned}
$$

Model overview

Parton showers

- Transverse-momentum-ordered parton showers
  - Dipole approach to recoil
  - Matching to ME for first emission in many processes
  - Well suited to POWHEG-type matching RC & T. Sjöstrand, arXiv:1003.2384, Eur. Phys. J. C69 (2010) 1–18
- ISR and MPI interleaved in PYTHIA 6
  - Competition for beam momentum
- FSR interleaved as well in PYTHIA 8
  - Much data well described
  - Problem with the underlying event?

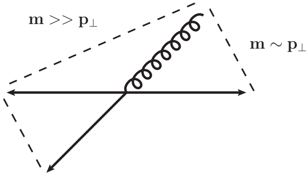


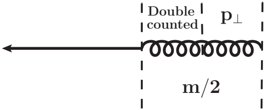


Model overview

Parton showers

- Final-state parton may have colour partner in the initial state
- How to subdivide FSR and ISR in this kind of dipole?
- Large mass $\rightarrow$ large rapidity range for emission
- Suppress final-state radiation in double-counted region





- Additional azimuthal weighting in ISR
  - Coherence effects implicit in $p_\perp$ ordering
  - Want recoil to build up $\rightarrow$ other incoming parton takes recoil
  - Weight based on expected angular distribution of soft emissions
  - Small effect

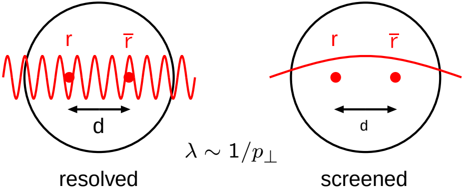
Model overview

MPI

- Ordered in decreasing $p_\perp$ using "Sudakov" trick

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right)$$

- QCD $2 \to 2$ cross section divergent in $p_\perp \to 0$ limit, but q/g not asymptotic states



- Regularise cross section, $p_{\perp 0}$ is now a free parameter

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

Model overview

MPI

- $p_{\perp 0}$ depends on energy
- Ansatz: scales in a similar manner to the total cross section (effective power related to the Pomeron intercept)

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^{E_{\mathrm{CM}}^{\mathrm{pow}}}$$

- Introduce impact parameter, b, with matter profile
  - Single Gaussian; no free parameters
  - Overlap function

$$\exp\left(-b^{E_{\mathrm{exp}}^{\mathrm{pow}}}\right)$$

  - Double Gaussian

$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3} \exp\left(-\frac{r^2}{a_2^2}\right)$$

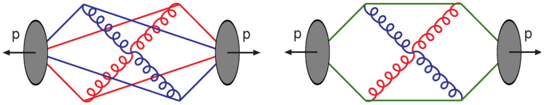
Model overview

Primordial $k_\perp$ and colour reconnection

- Primordial $k_\perp$
  - Needed for agreement with e.g. $p_\perp(\mathrm{Z}^0)$ distributions
  - Give all initiator partons Gaussian $k_\perp$, width

$$\sigma(Q, \widehat{m}) = \frac{Q_{\frac{1}{2}}\, \sigma_{\mathrm{soft}} + Q\, \sigma_{\mathrm{hard}}}{Q_{\frac{1}{2}} + Q} \; \frac{\widehat{m}}{\widehat{m}_{\frac{1}{2}} + \widehat{m}}$$

- Colour reconnection: rearrangement of final-state colour connections such that overall string length is reduced



- Large amount of reconnection required for agreement with data
- Probability for a system to reconnect with a harder system

$$\mathcal{P} = \frac{p_{\perp R}^2}{(p_{\perp R}^2 + p_\perp^2)}\,, \qquad p_{\perp R} = R * p_{\perp 0}^{\mathrm{MI}}$$

Model overview

Total cross sections

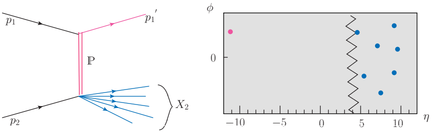
- Total cross sections
  - Total cross section using DL parameterisation
  - Schuler-Sjöstrand: regge theory and empirical corrections to limit growth of diffractive and elastic cross sections
  - Need to dampen diffractive rates further?
    Simple scheme to slow growth

$$\sigma^{\mathrm{mod}}(s) = \frac{\sigma^{\mathrm{old}}(s)\ \sigma^{\mathrm{max}}(s)}{\sigma^{\mathrm{old}}(s) + \sigma^{\mathrm{max}}(s)}$$

Model overview

Diffraction

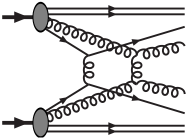
- Move from INEL/NSD $\rightarrow$ INEL$>$0 datasets
  - Reproducible definitions!
  - Diffractive description more important
- Soft description same as in PYTHIA 6
  - Pomeron kicks out valence quark or gluon from the proton
- New high-mass diffractive framework using Ingelman-Schlein picture
  - “Diffraction in Pythia,” S. Navin, arXiv:1005.3894 [hep-ph]
- Single diffraction
  - Proton emits Pomeron according to Pomerom PDF, $f_{\mathbb{P}/p}(x_{\mathbb{P}}, t)$
  - Pomeron–proton collision using the full machinery of proton–proton collisions

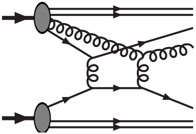


- Double diffraction: two Pomeron–proton collisions

Rescattering

- MPI traditionally disjoint $2 \to 2$ interactions
- Rescattering: allow an already scattered parton to interact again





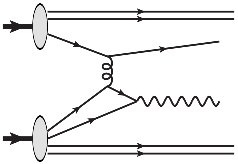
- Investigated by Paver and Treleani (1984), size of effect small, but should be there!
  - Plays a role in the collective effects of MPI
  - Possible colour connection effects
- Typical case of small angle scatterings between partons from 2 incoming hadrons, such that they are still associated with their original hadrons

$$f(x, Q^2) \to f_{\mathrm{rescaled}}(x, Q^2) + \sum_n \delta(x - x_n)$$

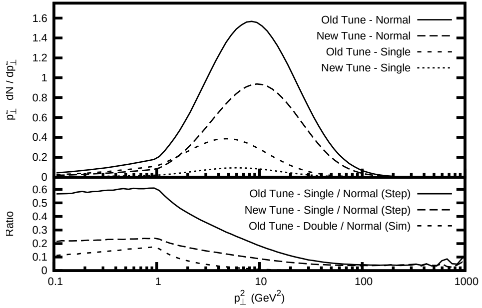
- Original MPI interactions supplemented by:
  - Single rescatterings: one parton from the rescaled PDF, one delta function
  - Double rescatterings: both partons are delta functions

Rescattering

- One simplification: rescatterings always occur at “later times”
  - Z^0 preceeded by rescattering not possible

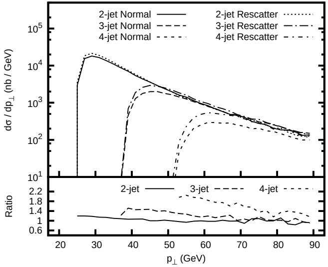


- In general not possible to uniquely identify a scattered parton with an incoming hadron, so use approximate rapidity based prescription
- Double rescattering always tiny, so ignored



Rescattering

- Hadron level
  - Feed results into FastJet, anti-$k_\perp$ algorithm, $R = 0.4$
  - 2-, 3- and 4-jet exclusive cross sections
  - Some increase in jet rates, but contributions can be "compensated" by changes in parameters elsewhere



pp, $\sqrt{s} = 14$ TeV, old tune, $p_\perp > 12.5$ GeV, $|\eta| < 1.0$

- Also studied
  - Colour reconnections
  - "Cronin" effect
  - ΔR & $\Delta\phi$ distributions
- No "smoking-gun" signatures for rescattering
- Would any effects be visible in a full tune?

x-dependent proton size

- Theoretical arguments and indirect evidence suggest wave function of high-x partons should be narrower than for small-x
- Pick width of single Gaussian matter profile based on x values

$$\rho(r) \propto \exp\left(-\frac{r^2}{\sigma^2(x)}\right)$$

$$\sigma(x) = a_0 + a_1 \ln\left(\frac{1}{x}\right)$$

- Convolution of two incoming protons

$$\mathcal{O}(b, x_1, x_2) \propto \frac{1}{\sigma_1^2(x_1) + \sigma_2^2(x_2)} \exp\left(-\frac{b^2}{\sigma_1^2(x_1) + \sigma_2^2(x_2)}\right)$$

- Consequences?
  - Width of multiplicity distributions
  - Rise of the underlying event
  - Possible to describe both together?

x-dependent proton size

- Generation of non-diffractive inelastic events ("min bias")
- Average number of interactions per event: $\langle n \rangle = \sigma_{\mathrm{hard}} / \sigma_{\mathrm{ND}}$
- Integrating out b, should be left where we started

$$\int \mathcal{O}(b, x_1, x_2) \, \mathrm{d}^2 b = 1$$

- Pick hardest interaction according to: $X = (x_1, x_2, p_\perp)$

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{hardest}}}{\mathrm{d}^2 b \, \mathrm{d}X} = p(X, b) \; \exp\left(- \int_{p_\perp}^{p_{\perp \mathrm{max}}} p(X', b) \, \mathrm{d}X' \right)$$

$$p(X, b) \propto \mathcal{O}(b, x_1, x_2) \, \frac{1}{\sigma_{\mathrm{ND}}} \, \frac{\mathrm{d}\sigma}{\mathrm{d}X}$$

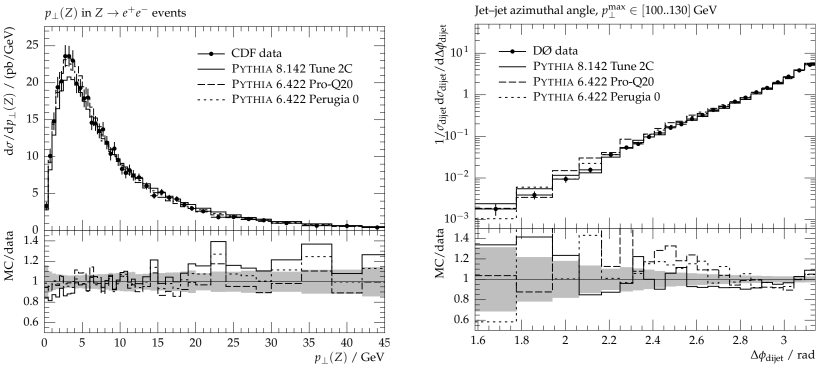
- b now fixed for subsequent downward $p_\perp$ evolution

Tuning prospects
Tevatron data

- FSR and hadronisatin tuned to LEP data (H. Hoeth)
- Identify key parameters and start with by-hand tune
- Compare to data (Rivet) and PYTHIA 6 Pro-Q20 and Perugia 0
- Tunes 2C (CTEQ6L1) and 2M (MRST LO**)
  - MRST LO** has more momentum: lower α_s and higher $p_{\perp 0}^{\mathrm{ref}}$ for MPI
  - Use overlap matter profile
  - Reduced colour reconnection relative to older tunes
  - Never significantly worse than Pro-Q20 or Perugia 0
  - More plots: `http://www.thep.lu.se/~richard/pythia81`

Tuning prospects

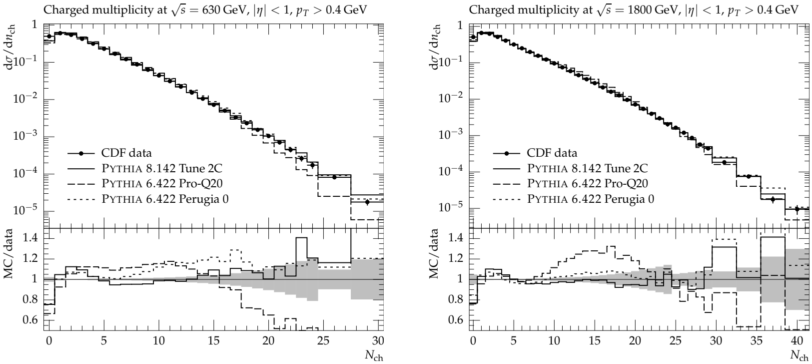
Tevatron data



- $p_\perp(Z^0)$ and jet-jet azimuthal angle help to disentangle ISR and MPI contributions
- Primordial $k_\perp$ has been left unchanged

Tuning prospects

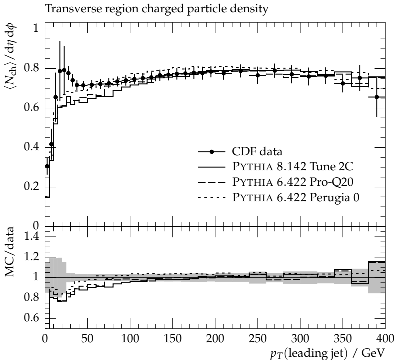
Tevatron data

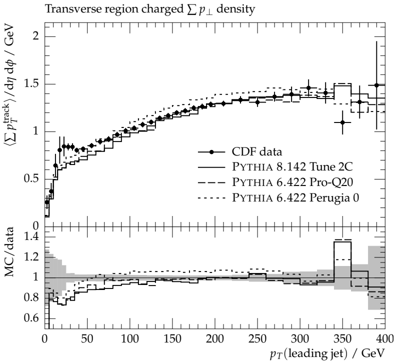


- Energy running of $p_{\perp 0}^{\mathrm{MPI}}$ only constrained by Tevatron $\sqrt{s} = 630\ \mathrm{GeV}$ multiplicity data
- $E_{\mathrm{exp}}^{\mathrm{pow}}$ affects impact-parameter fluctuations $\rightarrow$ high multiplicity tails

Tuning prospects

Tevatron data





- Large rise of UE now gone!
- $E_{\mathrm{exp}}^{\mathrm{pow}}$ affects how steeply the underlying event rises

Tuning prospects

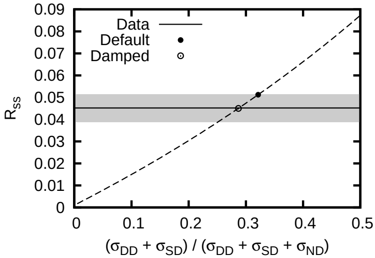
LHC data: diffractive cross sections

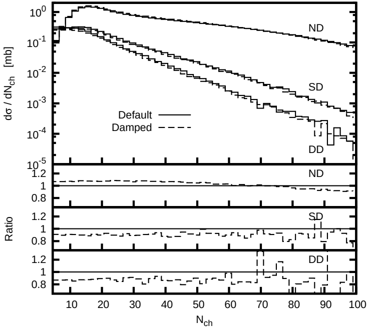
- Recent diffractive study: ATLAS-CONF-2010-048
  - New high-mass diffractive framework improves track description
  - Ratio of single-side hits in minimum-bias trigger scintillator to either side

$$R_{\mathrm{ss}}^{\mathrm{data}} = [4.52 \pm 0.02(\mathrm{stat}) \pm 0.61(\mathrm{syst})]\%$$
$$R_{\mathrm{ss}}^{\mathrm{PY}} = 5.11\%$$

- Assume single- and double-diffractive cross sections saturate at the same value

$$\sigma_{\mathrm{SD}}^{\mathrm{max}} = \sigma_{\mathrm{DD}}^{\mathrm{max}} = 65 \text{ mb}$$





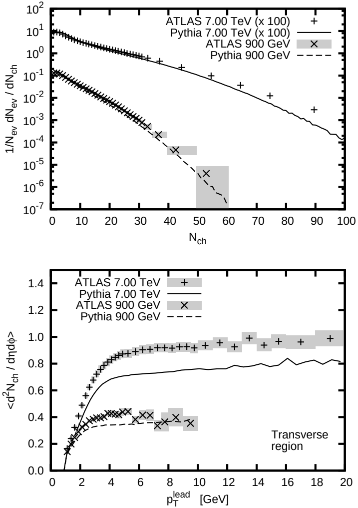
Tuning prospects

LHC data: minimum bias and underlying event

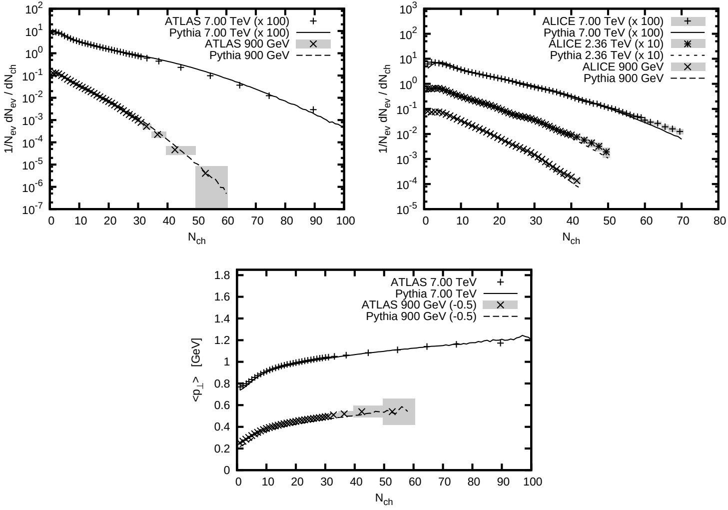
- Pick key sets of MB/UE data
  - Take from HEPDATA where possible
  - Read off plots if necessary
- Use Tune 2C as a starting point
  - Dampen diffractive cross sections as in previous slide
  - Only vary MPI and colour reconnection parameters
- Tune 4C
  - Take $\langle p_\perp \rangle (N_\mathrm{ch})$ seriously $\rightarrow$ less colour reconnection
  - But consequences elsewhere, e.g. rise in transverse number density not matched by $\sum p_\perp$ density
  - Back to single Gaussian matter profile, but still slightly too fast a rise in UE
  - Overall reasonable description; expect better from a full tuning?

Tuning prospects

LHC data: minimum bias and underlying event



Tune 2C

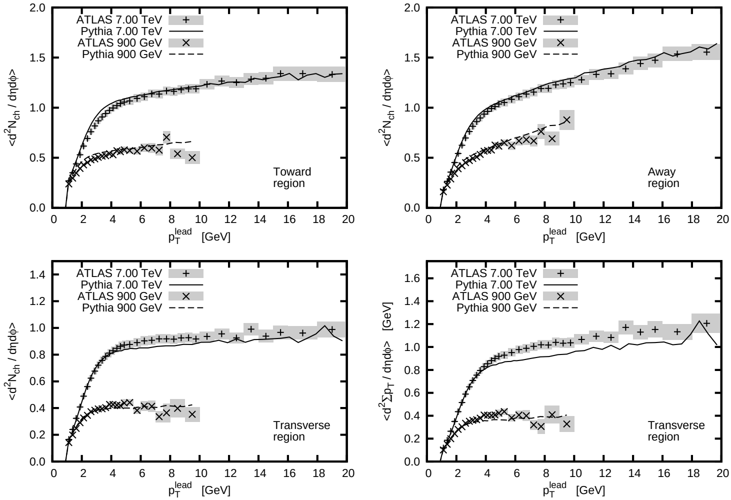


ATLAS 7.00 TeV (x 100)
Pythia 7.00 TeV (x 100)
ATLAS 900 GeV
Pythia 900 GeV
1/N_ev dN_ev / dN_ch
N_ch
ALICE 7.00 TeV (x 100)
Pythia 7.00 TeV (x 100)
ALICE 2.36 TeV (x 10)
Pythia 2.36 TeV (x 10)
ALICE 900 GeV
Pythia 900 GeV
1/N_ev dN_ev / dN_ch
N_ch
ATLAS 7.00 TeV
Pythia 7.00 TeV
ATLAS 900 GeV (-0.5)
Pythia 900 GeV (-0.5)
<p_⊥> [GeV]
N_ch

Tune 4C

Tuning prospects

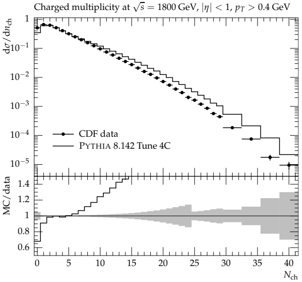
LHC data: minimum bias and underlying event

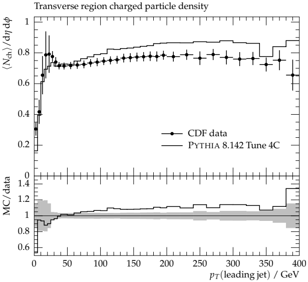


Tune 4C

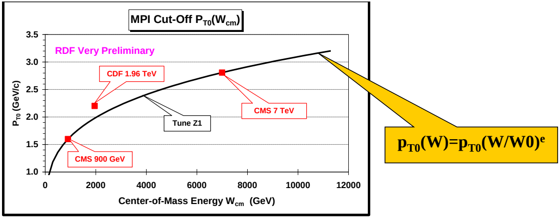
Tuning prospects

LHC data: minimum bias and underlying event





- Tune 4C at the Tevatron gives too much activity
- Similar to Rick Field and Tune Z1?



Conclusions

- Well established MPI model, but still trying new things!
  - Rescattering
  - *x*-dependent proton size
- "Interleaved Parton Showers and Tuning Prospects," RC and T. Sjöstrand, arXiv:1011.1759 [hep-ph].
- Modest changes to PS framework
  - Greatly improves underlying-event description at the Tevatron
  - Simultaneous MB/UE tunes possible
- First LHC data
  - Comparison to ATLAS/ALICE MB/UE data
  - Very limited tuning, but reasonable agreement
  - Signs of tension within the data? e.g. $\langle p_{\perp} \rangle (N_{\mathrm{ch}})$
- Simultaneous Tevatron/LHC tune
  - Looks like it will be difficult, but may be regions in parameter space where possible to some extent
  - Experimental issues? Model issues? (e.g. energy running of parameters)
  - Look forward to more data to help resolve the issue

Backup slides

Tunes

Parameter	Tune 2C	Tune 2M	Tune 4C
SigmaProcess:alphaSvalue	0.135	0.1265	0.135
SpaceShower:rapidityOrder	on	on	on
SpaceShower:alphaSvalue	0.137	0.130	0.137
SpaceShower:pT0Ref	2.0	2.0	2.0
MultipleInteractions:alphaSvalue	0.135	0.127	0.135
MultipleInteractions:pT0Ref	2.320	2.455	2.085
MultipleInteractions:ecmPow	0.21	0.26	0.19
MultipleInteractions:bProfile	3	3	3
MultipleInteractions:expPow	1.60	1.15	2.00
BeamRemnants:reconnectRange	3.0	3.0	1.5
SigmaDiffractive:dampen	off	off	on
SigmaDiffractive:maxXB	N/A	N/A	65
SigmaDiffractive:maxAX	N/A	N/A	65
SigmaDiffractive:maxXX	N/A	N/A	65