Workshop on Hadron-Hadron & Cosmic-Ray
Interactions at multi-TeV Energies
29 Nov – 3 Dec 2010
ECT*, Trento, Italy

PYTHIA 8 Status

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Improvements, especially for MB/UE, relative to PYTHIA 6
Tuning of MB/UE physics
Non-explanation of CMS ridge effect
Future plans

Ambition

- Meet experimental request for C++ code.
- Housecleaning $\Rightarrow$ more homogeneous.
- More user-friendly (e.g. settings names).
- Better match to software frameworks (e.g. card files).
- More space for growth.
- Better interfaces to external standards.

Reality

- Work begun autumn 2004.
- 3 years at CERN $\Rightarrow$ good progress.
- First release autumn 2007.
- Since then: slower progress, requests lagging behind.
- Slow adoption (rightfully so?).

Team members

Stefan Ask
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Contributors

Bertrand Bellenot
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Philip Ilten
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MSTW, CTEQ, H1: PDFs
DELPHI, LHCb: D/B BRs
+ several bug reports & fixes

Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:

- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:

- ep, γp and $\gamma\gamma$ beam configurations
- several processes, especially Technicolor, partly SUSY

New features, not found in 6.4 ($\star$ = see below):

$\star$ interleaved $p_{\perp}$-ordered MPI + ISR + FSR evolution
- richer mix of underlying-event processes (γ, J/ψ, DY, ...)

$\star$ possibility for two selected hard interactions in same event
$\star$ allow rescattering in MPI framework
$\star$ hard scattering in diffractive systems
- several new processes, within and beyond SM
- possibility to use one PDF set for hard process and another for rest
- updated decay data and LO PDF sets

Interleaved evolution

- Transverse-momentum-ordered parton showers for ISR and FSR
- MPI also ordered in $p_\perp$

Allows interleaved evolution for ISR, FSR and MPI

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

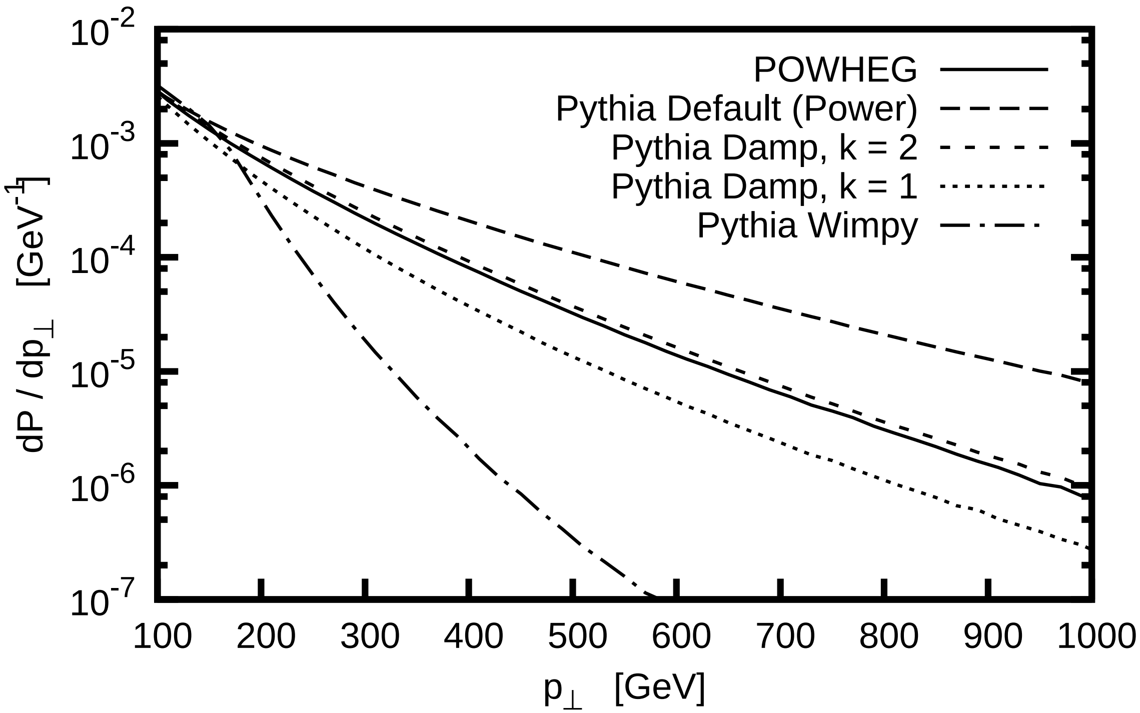
Ordered in decreasing $p_\perp$ using “Sudakov” trick.
Corresponds to increasing “resolution”:
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

Hybrid approach to shower recoils:

- FSR is dipole: nearest colour-connected neighbour
- ISR is traditional: whole hard-scattering system affected
  (since ISR dipole gives wrong answer e.g. for $p_{\perp Z}$)

Shower matching to MEs – I

Aim: provide better default shower behaviour at large $p_\perp$, to bridge gap between “power” and “wimpy” showers.



$t\bar{t}$ production

$$M^2 = m_{\perp t}^2 = m_t^2 + p_{\perp t}^2$$

$$\frac{\mathrm{d}P_{\mathrm{ISR}}}{\mathrm{d}p_\perp^2} \propto \frac{1}{p_\perp^2} \frac{k^2 M^2}{k^2 M^2 + p_\perp^2}$$ for coloured final state

No dampening for uncoloured final state (W^+W^-, . . . , SUSY).

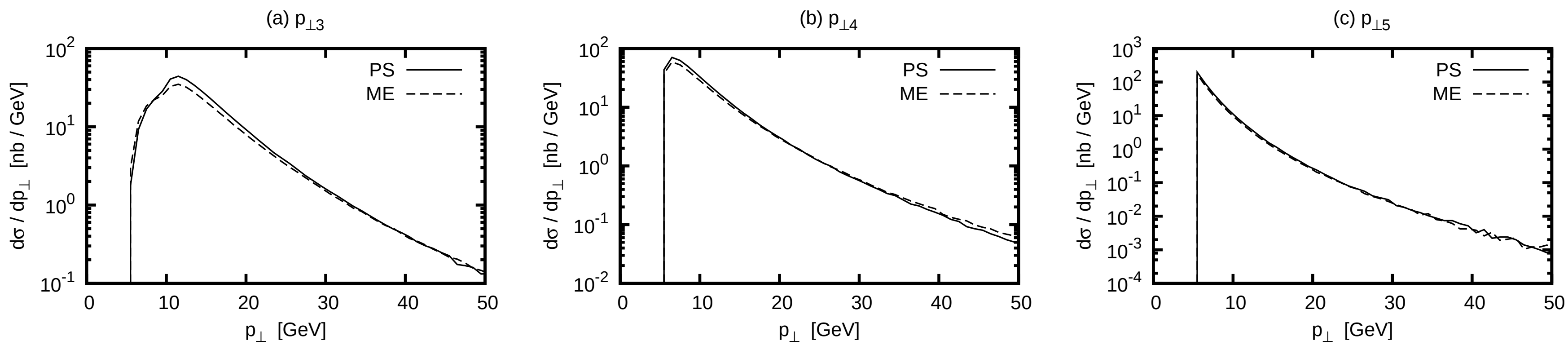
R. Corke & TS, Eur. Phys. J. C69 (2010) 1

(+ improved interfacing to POWHEG, . . .)

Shower matching to MEs – II

Must avoid doublecounting for QCD jets:
shower starting scale = $p_\perp$ of hard $2 \to 2$ process.

Study how well the parton shower fills the phase space,
as prelude to full matching to $2 \to 3$ real-emission:



$$p_{\perp 3}^{\text{min}} = 5.0\ \text{GeV},\ p_{\perp 4}^{\text{min}} = 5.0\ \text{GeV},\ R_{\text{sep}} = 0.10$$

Obtain good qualitative agreement, best in soft and collinear regions,
but large region of phase space well described, and only corners bad.
No indication for needing a change in starting scale!

Multiparton interactions

Regularise cross section with $p_{\perp 0}$ as free parameter

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

with energy dependence

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

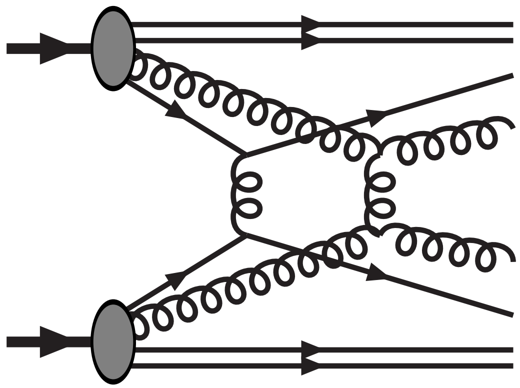
Matter profile in impact-parameter space
gives time-integrated overlap which determines level of activity:
simple Gaussian or more peaked variants

ISR and MPI compete for beam momentum $\to$ PDF rescaling
$+$ flavour effects (valence, $\mathrm{q}\overline{\mathrm{q}}$ pair companions, ...)
$+$ correlated primordial $k_\perp$ and colour in beam remnant

Many partons produced close in space–time $\Rightarrow$ colour rearrangement;
reduction of total string length $\Rightarrow$ steeper $\langle p_\perp \rangle(n_{\mathrm{ch}})$

A second hard process

Multiple interactions key aspect
of PYTHIA since >20 years.
Central to obtain agreement with data:
Tune A, Professor, Perugia, ...



Before 8.1 no chance to select character of second interaction.
Now free choice of first process (including LHA/LHEF)
and second process combined from list:

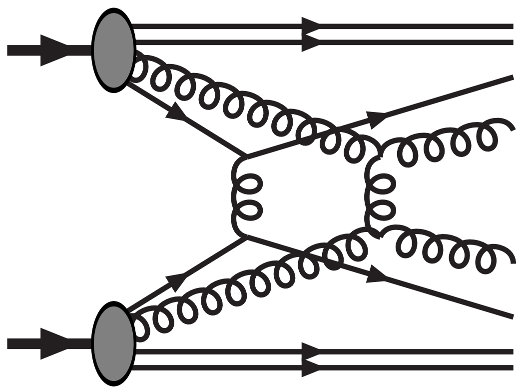
- TwoJets (with TwoBJets as subsample)
- PhotonAndJet, TwoPhotons
- Charmonium, Bottomonium (colour octet framework)
- SingleGmZ, SingleW, GmZAndJet, WAndJet
- TopPair, SingleTop

Can be expanded among existing processes as need arises.

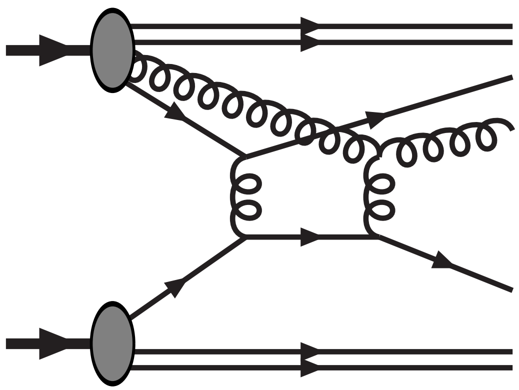
By default same phase space cuts as for "first" hard process
$\Longrightarrow$ second can be harder than first.
However, possible to set $\hat{m}$ and $\hat{p_\perp}$ range separately.

Rescattering

Often assume that MPI =



. . . but should also include



Same order in α_s, $\sim$ same propagators, but

- one PDF weight less $\Rightarrow$ smaller σ
- one jet less $\Rightarrow$ QCD radiation background $2 \to 3$ larger than $2 \to 4$

$\Rightarrow$ will be tough to find direct evidence.

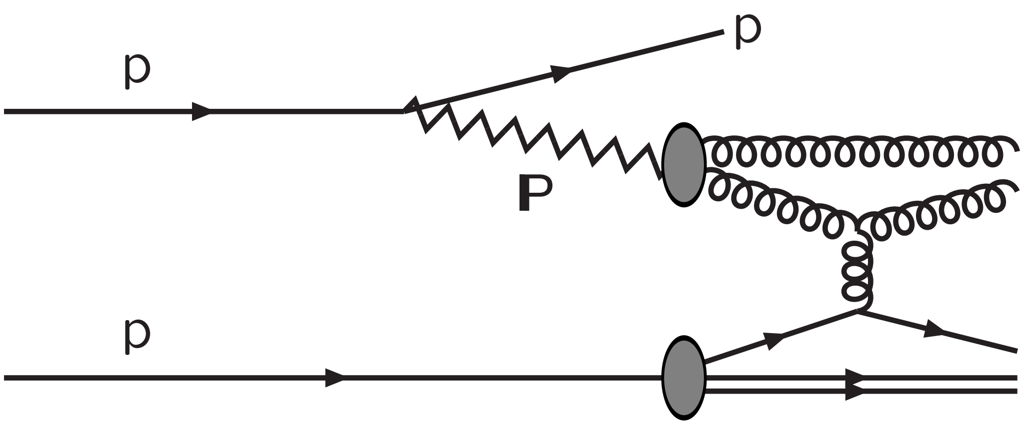
Rescattering grows with number of “previous” scatterings:

	Tevatron		LHC	
	Min Bias	QCD Jets	Min Bias	QCD Jets
Normal scattering	2.81	5.09	5.19	12.19
Single rescatterings	0.41	1.32	1.03	4.10
Double rescatterings	0.01	0.04	0.03	0.15

R. Corke & TS, JHEP 01 (2010) 035 [arXiv:0911.1909]

Diffraction

Ingelman-Schlein: Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) $\times$ ($\mathbb{P}$p collision)



Used e.g. in

POMPYT

POMWIG

PHOJET

1) σ_{SD} and σ_{DD} taken from existing parametrization or set by user.

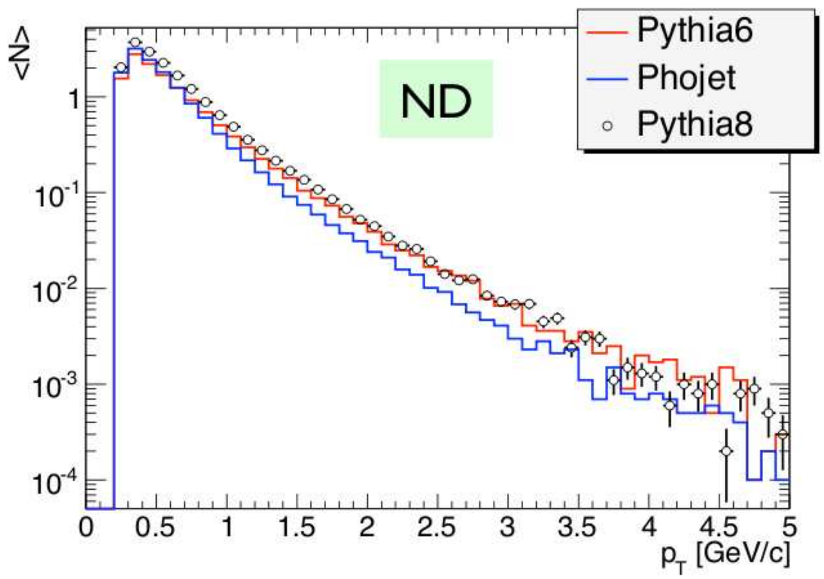
2) Shape of Pomeron distribution inside a proton, $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)$ gives diffractive mass spectrum and scattering $p_{\perp}$ of proton.

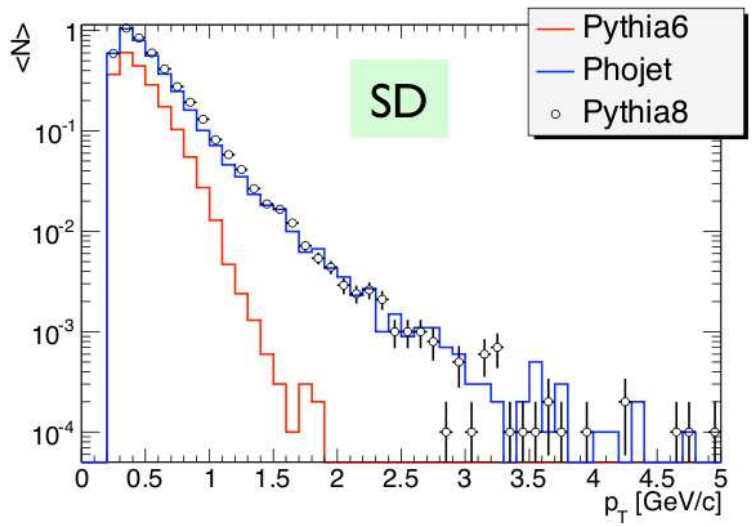
3) At low masses retain old framework, with longitudinal string(s). Above 10 GeV begin smooth transition to $\mathbb{P}$p handled with full pp machinery: multiple interactions, parton showers, beam remnants, ...

4) Choice between 5 Pomeron PDFs. Free parameter $\sigma_{\mathbb{P}\mathrm{p}}$ needed to fix $\langle n_{\mathrm{interactions}} \rangle = \sigma_{\mathrm{jet}}/\sigma_{\mathbb{P}\mathrm{p}}$.

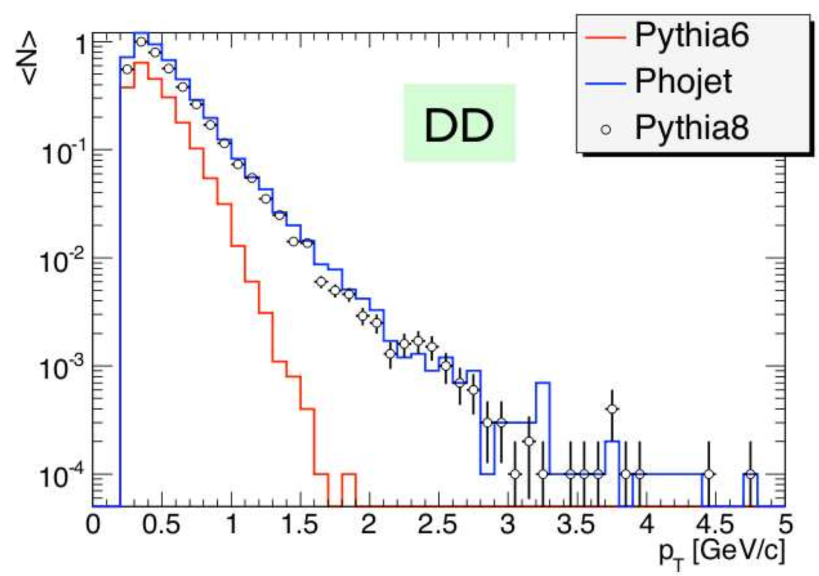
5) Framework needs testing and tuning, e.g. of $\sigma_{\mathbb{P}\mathrm{p}}$.

p_T Distributions ($\sqrt{s}$=0.9 TeV)





- Softer p_T spectrum in **Pythia6** due to lack of high mass diffraction
- **Pythia8** and **Phojet** agree quite well

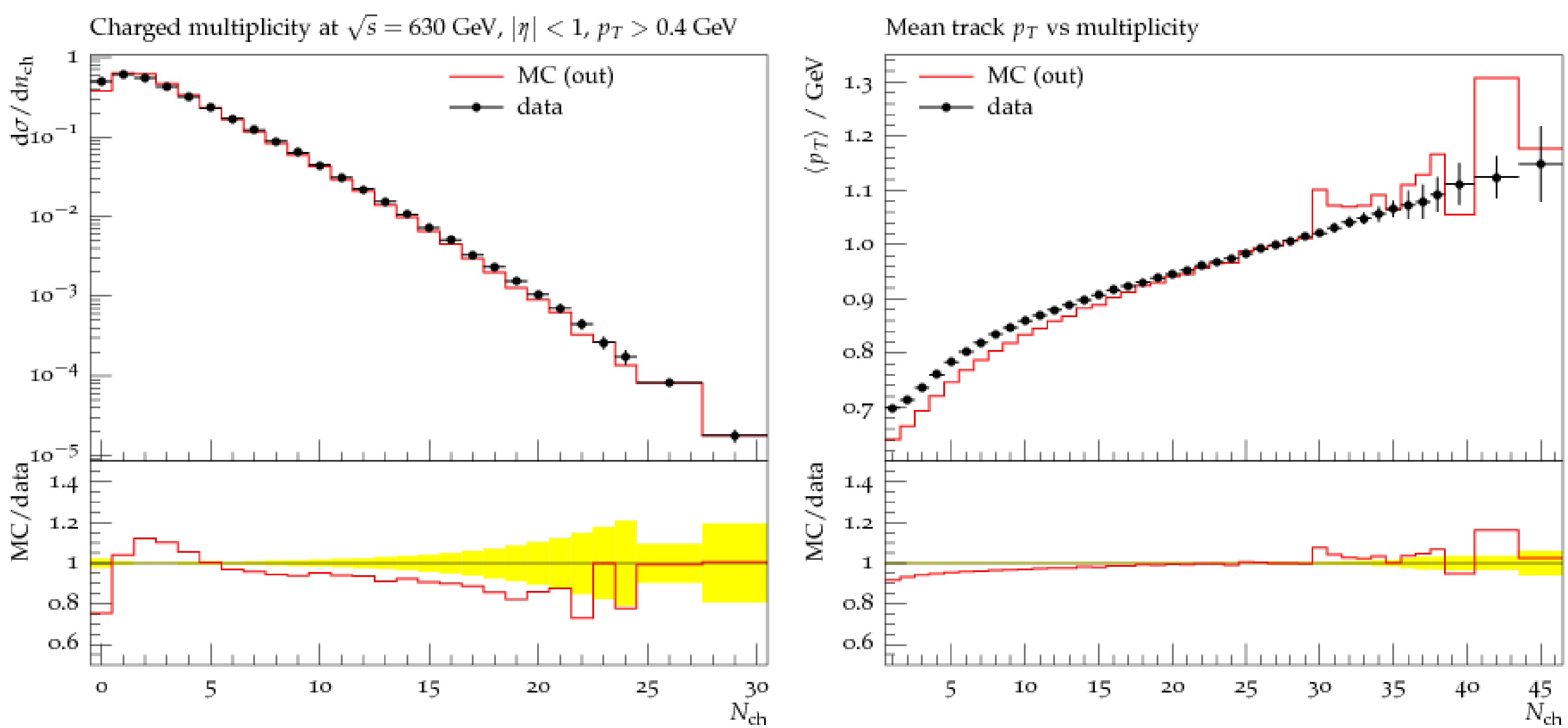


Beate Heinemann, MB/UE Working Group, March 1 (also Sparsh Navin)

Tuning prospects

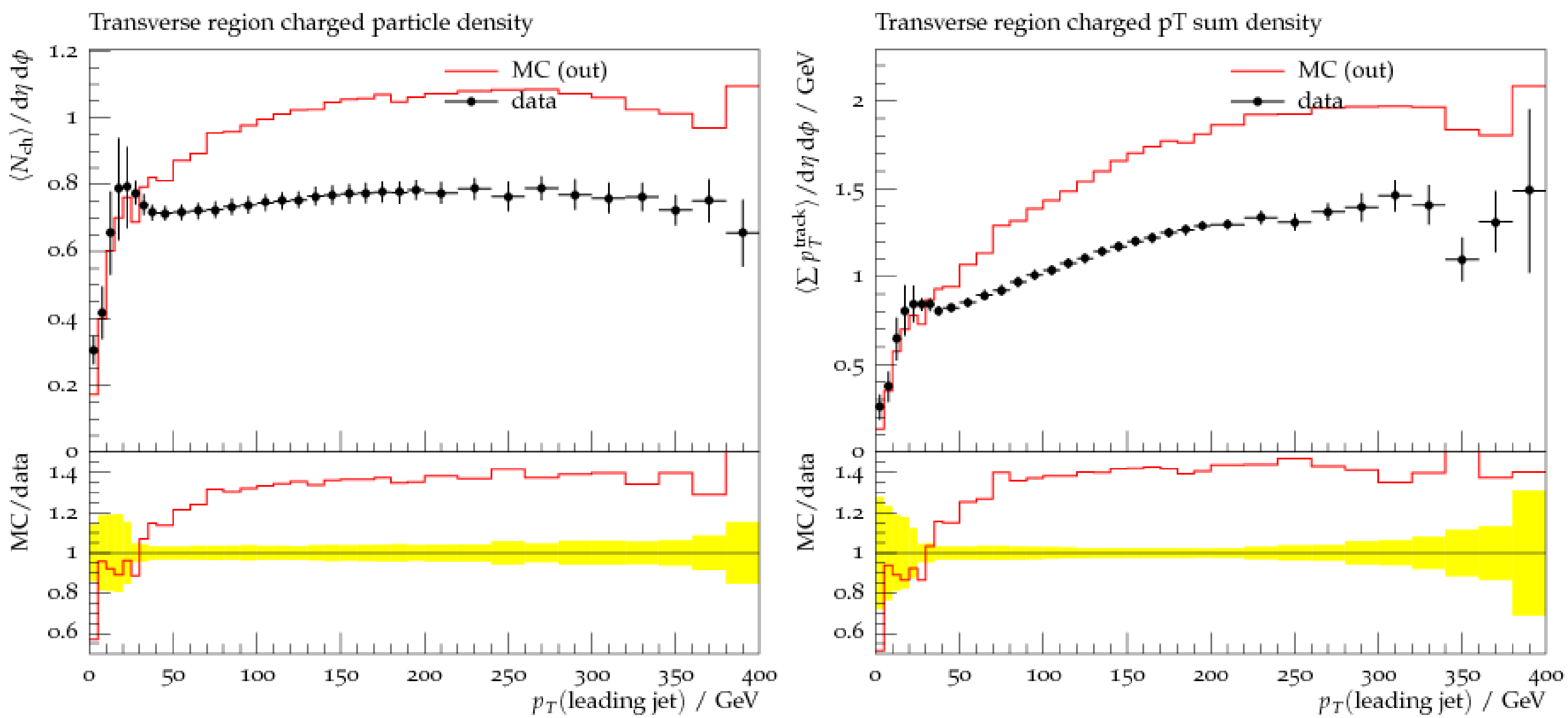
Tuning to e^+e^- closely related to $p_\perp$-ordered PYTHIA 6.4;
Rivet+Professor (H. Hoeth) ⇒ FSR & hadronization OK (?)

First tuning to MB data by P. Skands:



⇒ MPI & colour reconnection OK (?)

But Rivet+Professor (H. Hoeth) shows it fails miserably for UE
(Rick Field's transverse flow as function of jet $p_\perp$):



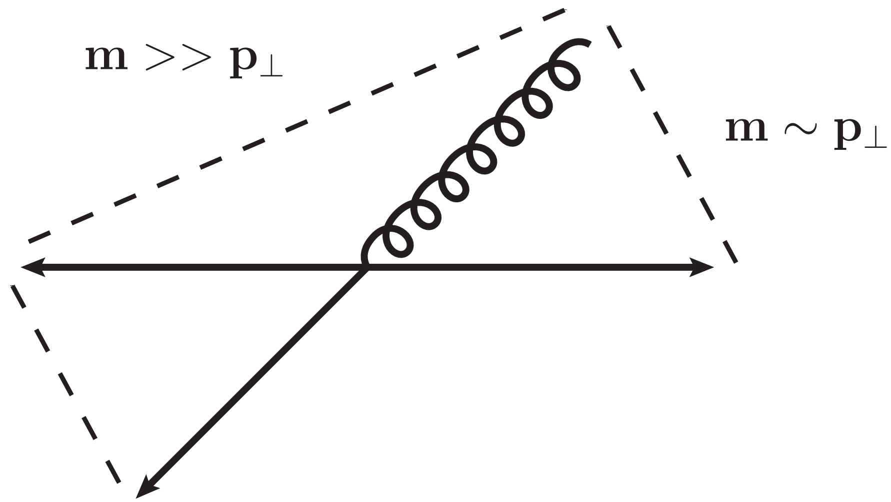
No universal tune MB + UE!

Where did we go wrong?

Final-state parton may have colour partner in the initial state.

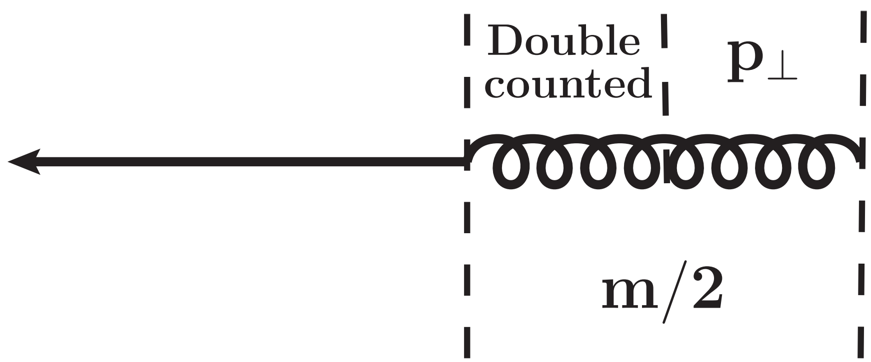
How to subdivide FSR and ISR in this kind of dipole?

Large mass $\longrightarrow$ large rapidity range for emission:



In dipole rest frame

(think rapidity space)

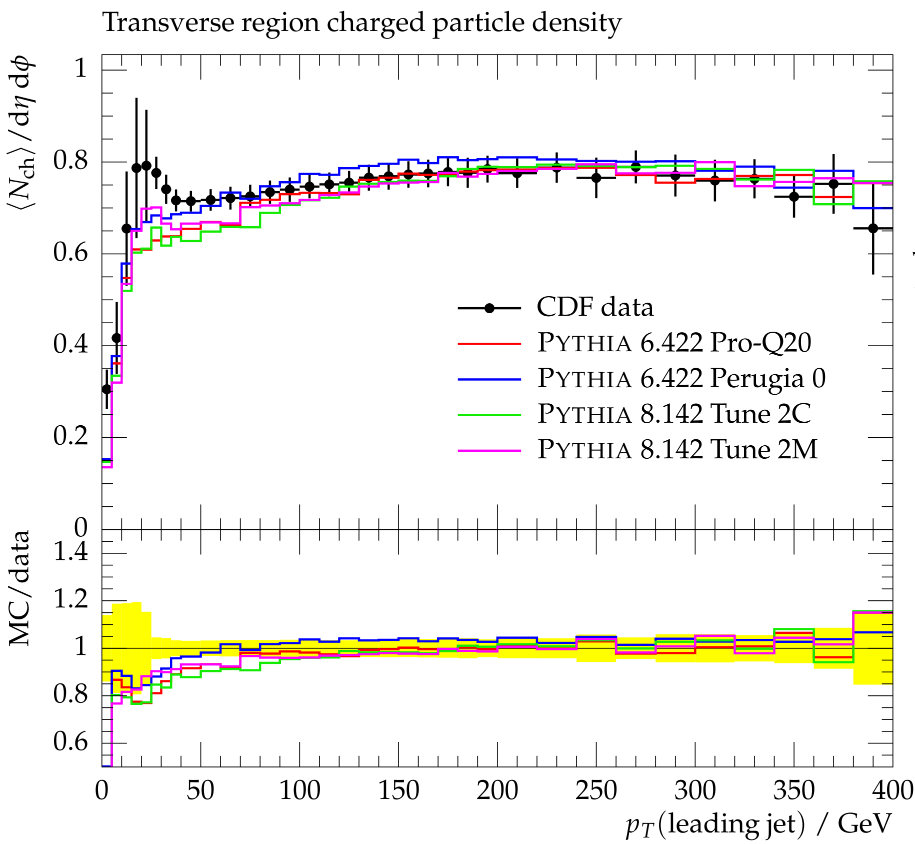


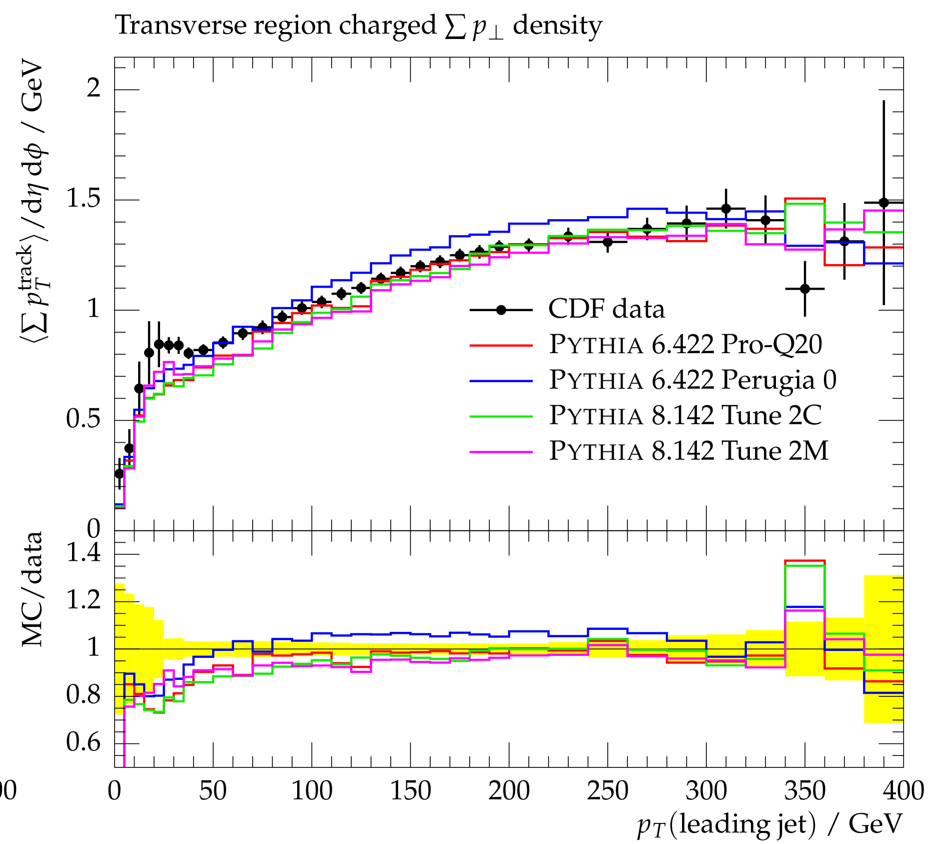
Solution: suppress final-state radiation in double-counted region

Is a simultaneous MB/UE Tevatron tune now possible?

Tunes 2C and 2M done “by hand” (= using Rivet, but not Professor), using the CTEQ6L1 and MRST LO** PDF sets, respectively, to MB data (n_{ch}, $\langle p_\perp \rangle(n_{\mathrm{ch}})$, ...

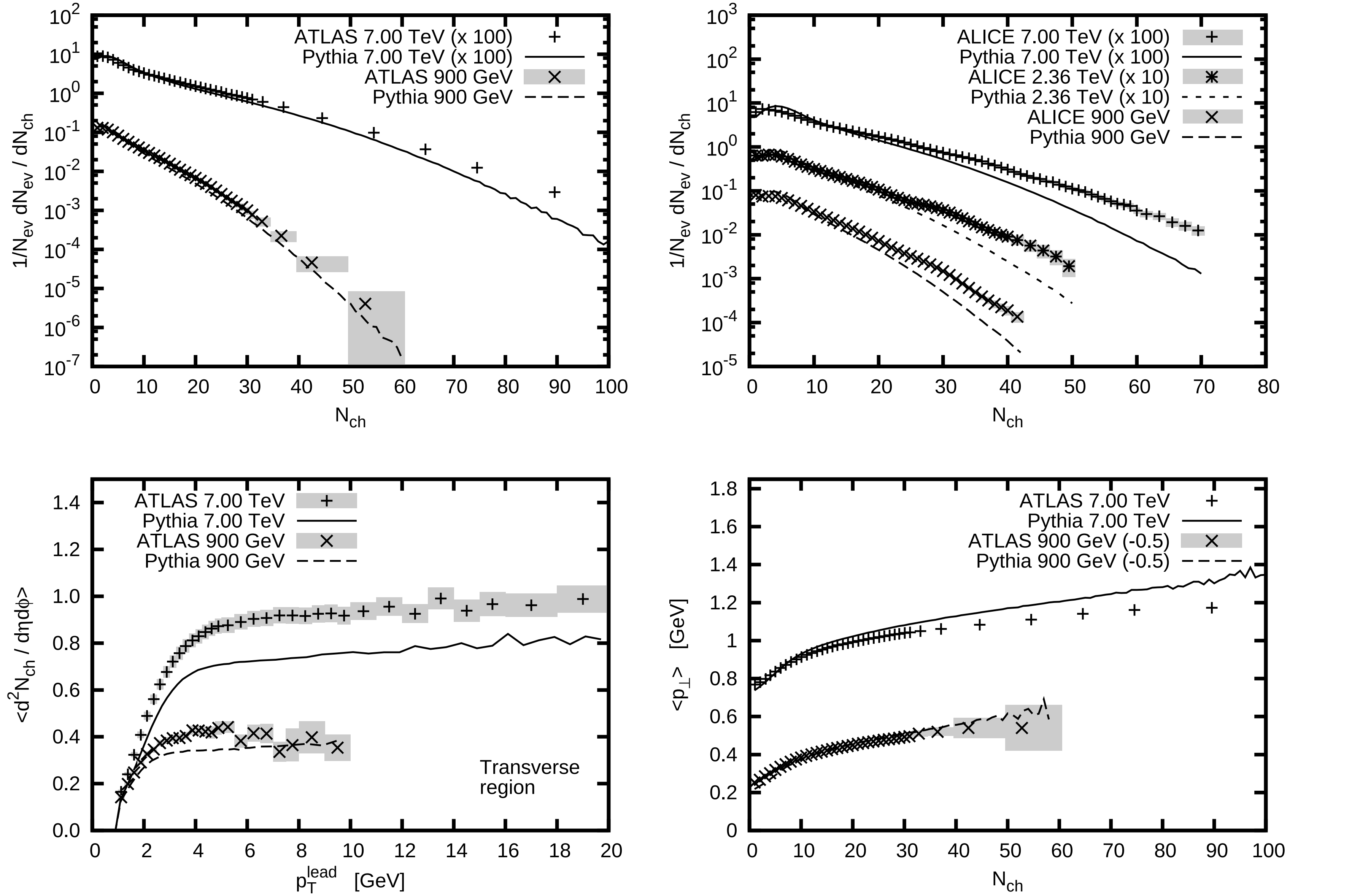
Compare against Pro-Q20 and Perugia 0 (PYTHIA6)





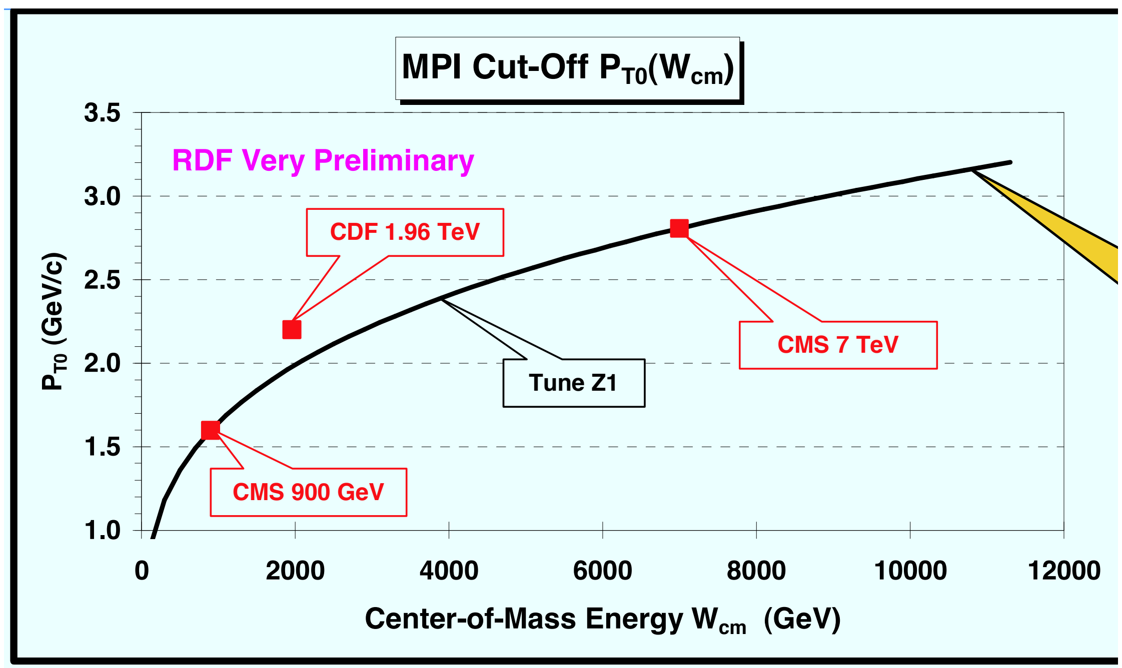
Now generally comparably good description to old tunes at the Tevatron.

Tune 2C applied to LHC data does not do so good:



Tension between Tevatron and LHC data?

Rick Field: if $p_{\perp 0}(E_{\mathrm{CM}}) \propto E_{\mathrm{CM}}^{\epsilon}$ tuned to LHC data, then gives too much UE activity at Tevatron
($\Rightarrow$ need higher $p_{\perp 0}$ to compensate)



Pick some key LHC data sets, use Tune 2C as starting point:

- slightly dampen diffractive cross section (ATLAS)
- only vary MPI and colour reconnection parameters

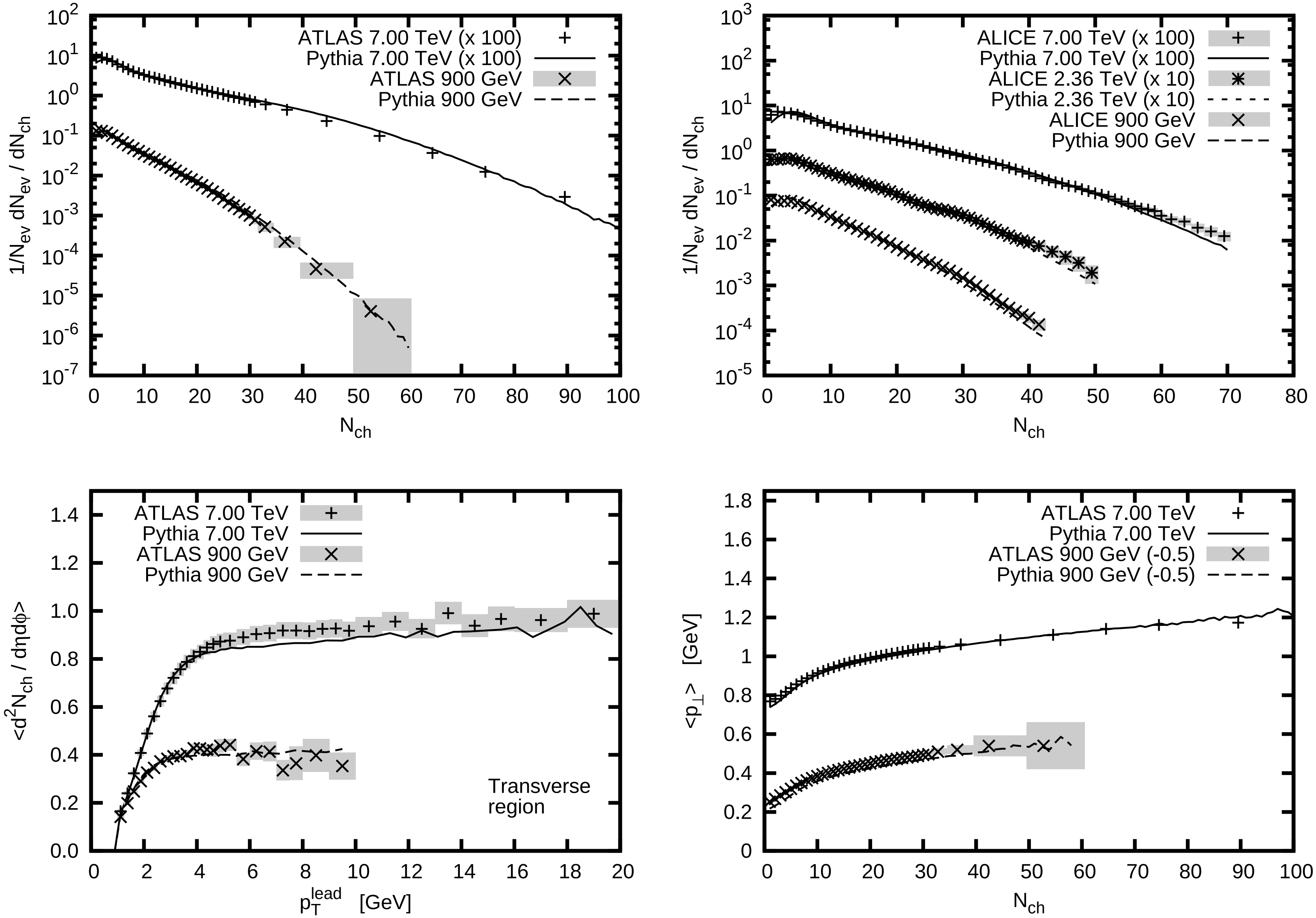
New tunes

. . . while waiting for LHC data conveniently implemented in Rivet.

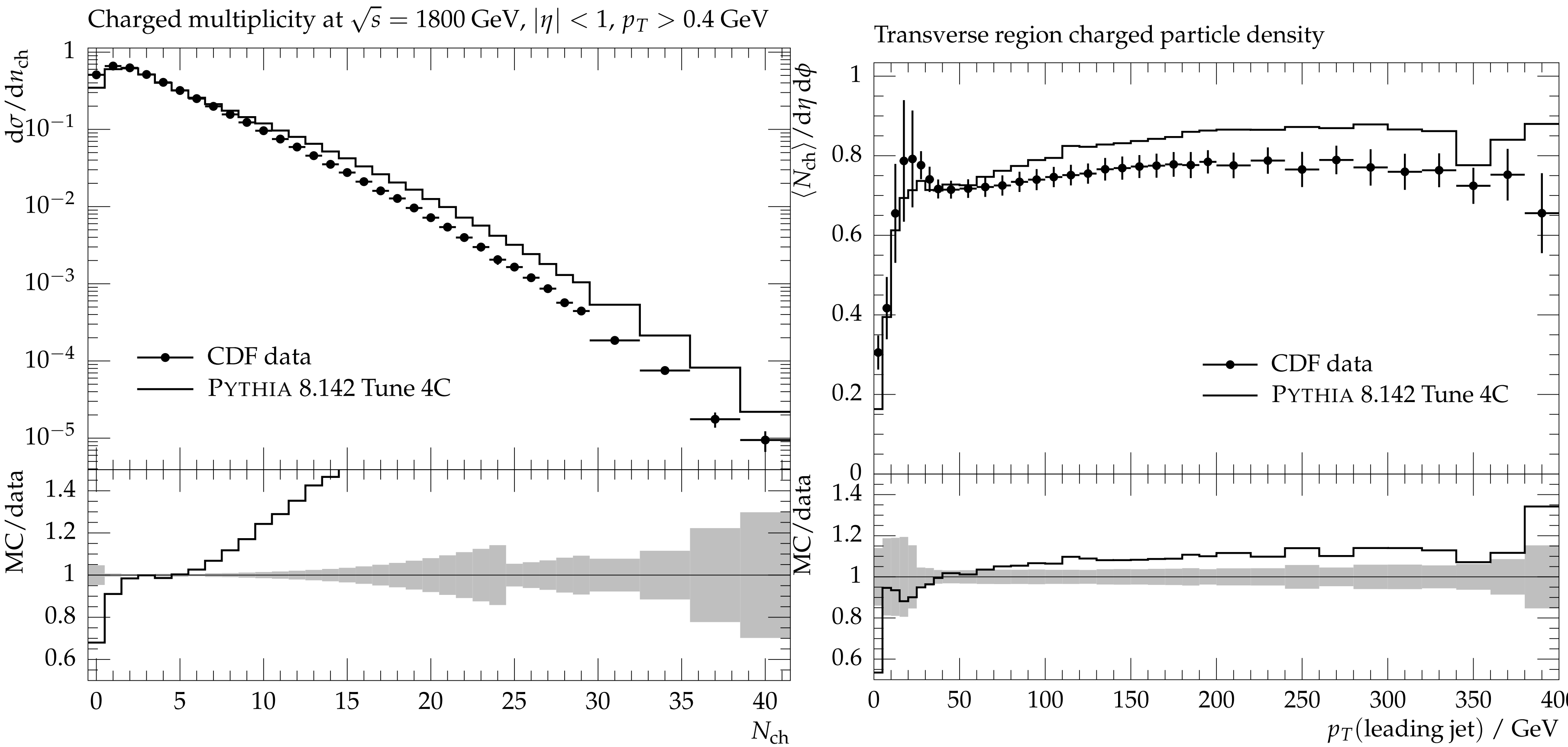
Parameter	Tune 2C	Tune 2M	Tune 4C
`SigmaProcess:alphaSvalue`	0.135	0.1265	0.135
`SpaceShower:rapidityOrder`	on	on	on
`SpaceShower:alphaSvalue`	0.137	0.130	0.137
`SpaceShower:pT0Ref`	2.0	2.0	2.0
`MultipleInteractions:alphaSvalue`	0.135	0.127	0.135
`MultipleInteractions:pT0Ref`	2.320	2.455	2.085
`MultipleInteractions:ecmPow`	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

R. Corke & TS, arXiv:1011.1759 [hep-ph]

Tune 4C now describes LHC data reasonably well:



. . . but at the expense of Tevatron agreement:



Future:

- better understanding of data?
- official/validated inclusion in Rivet?
- combined tune Tevatron + LHC?

Some thoughts on the CMS ridge effect

Warning: I do not know the solution!
It is not reproduced/explained by PYTHIA!

Impact parameter b crucially important in heavy-ion collisions.
Also needed e.g. for MPI to give a broad enough multiplicity distribution.
This defines a collision plane, and thereby possibly azimuthal anisotropies.

- additional pressure in plane $\Rightarrow$ faster expansion (HI) ?
- orbital angular momentum conservation ?

(K.G. Boreskov, A.B. Kaidalov, O.V. Kancheli, Eur.Phys.J.C58 (2008) 445;
P. Van Mechelen, private communication)

- other mechanisms

Effects automatically spread over whole rapidity range,
should give fairly broad enhancement in φ.

But should then disappear at the largest multiplicities,
where impact parameter is close to zero:

n_{ch}	$\langle b \rangle \pm \sigma_b$	n_{event}
0 — 5	1.31 ± 0.36	225273
6 — 10	1.21 ± 0.37	256050
11 — 20	0.96 ± 0.35	254323
21 — 40	0.64 ± 0.29	198726
41 — 70	0.40 ± 0.21	61572
71 — 100	0.28 ± 0.16	3948
101 —	0.22 ± 0.12	108

$p_{\perp\text{hard}}$	$\langle b \rangle \pm \sigma_b$	n_{event}
0 — 5	1.14 ± 0.41	585416
5 — 10	0.83 ± 0.42	338272
10 — 20	0.73 ± 0.41	69539
20 — 40	0.71 ± 0.41	6326
40 —	0.67 ± 0.39	447

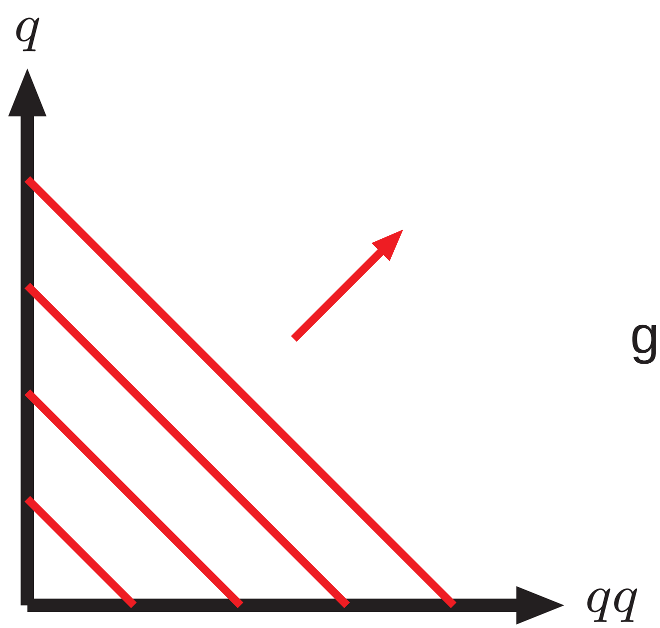
based on 10^6 “minbias” events, with PYTHIA 8.142 Tune 2C,
charged tracks in $|\eta| < 2.4$ and $p_\perp > 0.4$ GeV.
Normalization such that $\langle b \rangle \equiv 1$ for all “minbias” events.

Note: having one hard interaction does not bias as much as having a high charged multiplicity. You would need several hard ones to compete.

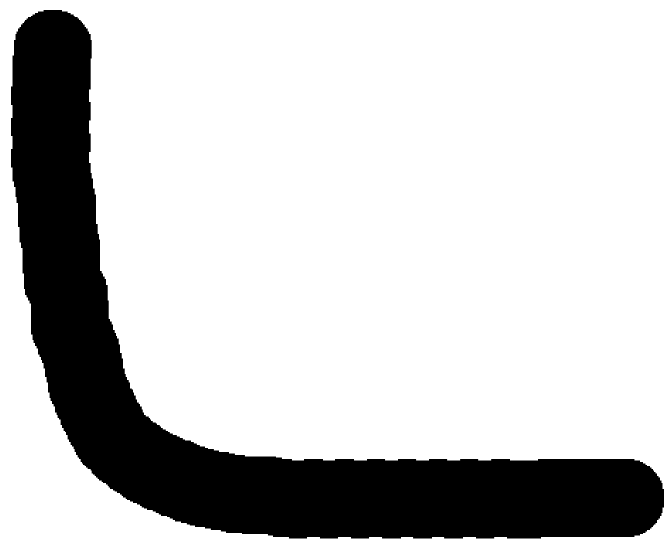
Way around (?): incoming proton state has elongated parton distribution
(C. Flensburg, G. Gustafson, L. Lönnblad)

String/dipole effects and the ridge

String fragmentation along boosted axis in space-time
gives hadrons along hyperbolic region in momentum space.



gives



Excellent way to obtain effect in $p_\perp$ range 1 – 3 GeV:

- higher-$p_\perp$ hadrons mainly along hard jet axis
- lower-$p_\perp$ hadrons mainly symmetric around beam jet axis

...but effect should die out like $\exp(-\Delta y)$ away from jet axis!

Similarly for dipoles stretched between high-$p_\perp$ partons and beams.

Suggestions for experimental analyses

1) Use a (mini)jet trigger.
Then look for a ridge in **low**-multiplicity events.
Reason: if dipole/string effect after all, it is set by the colour flow of the hardest interaction; further MPI will only dilute the primary effect.

2) Long-range correlations in (pseudo)rapidity, e.g. like UA5:

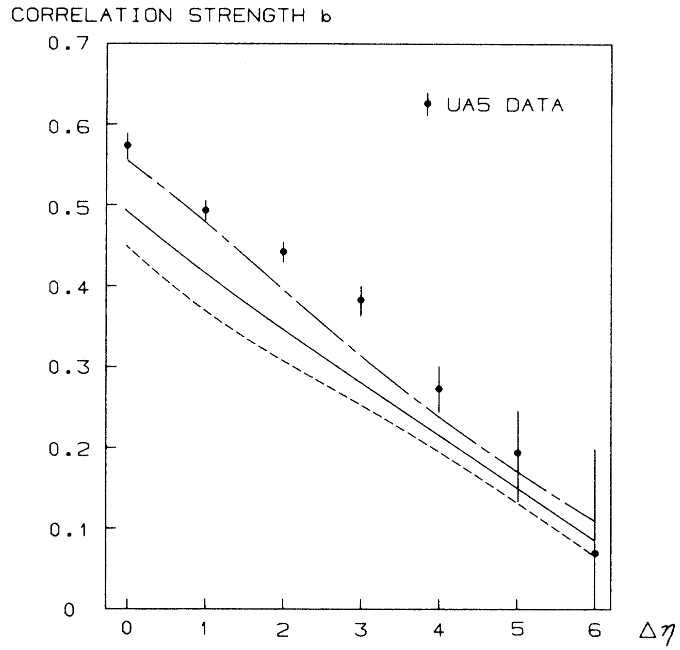
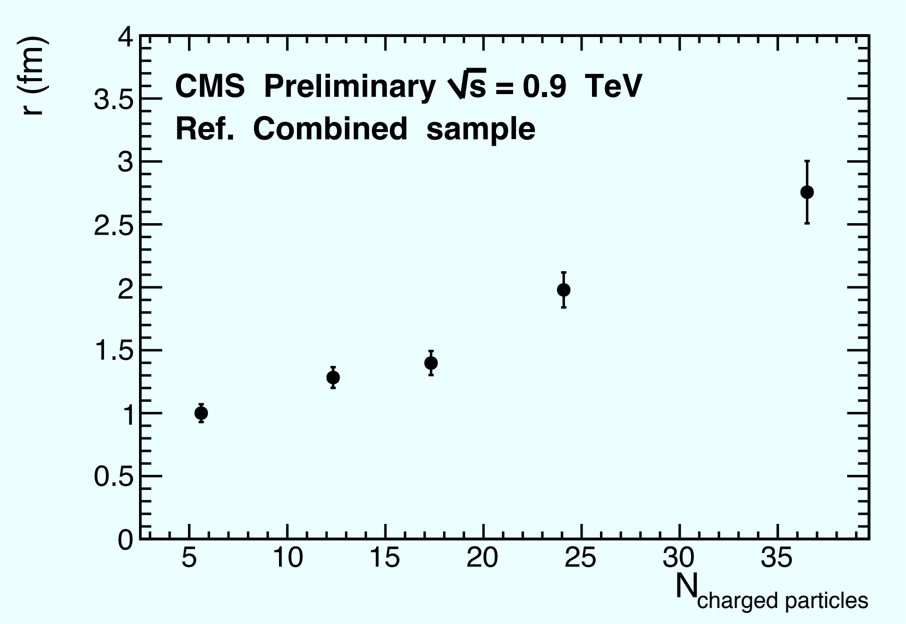


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.



3) Correlate ridge with asymmetric Bose-Einstein source.

Summary and Outlook

- PYTHIA6 is winding down:
  - ⋆ is supported but not developed;
  - ⋆ still main option for current run (sigh),
  - ⋆ *but not after long shutdown 2013*!
- PYTHIA8 is the natural successor,
  - ⋆ is (sadly!) not yet quite up to speed in *all* respects,
  - ⋆ but in others already better than PYTHIA6,
  - ⋆ is starting to have competitive tunes,
  - ⋆ and will continue to move ahead.
- Advise to experimentalists:
  - ⋆ start to use PYTHIA8 to build up experience;
  - ⋆ if you want new features (e.g. ψ', Υ') then be prepared to use PYTHIA8;
  - ⋆ provide feedback, both what works and what does not;
  - ⋆ do your own tunes to data and tell outcome.

There is no way back!