Studying Minijets and Multiple Particle Interactions with Rapidity Correlations

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in collaboration with
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based on arXiv:1808.06770

Slides prepared by A.Siodmok

Outline

1. Motivation

2. Multiple Particle Interactions (MPI) models in Monte Carlo Event Generators

3. New observable to study rapidity correlation of minijets

4. Summary and outlook

Motivation. How do we know MPI exists?

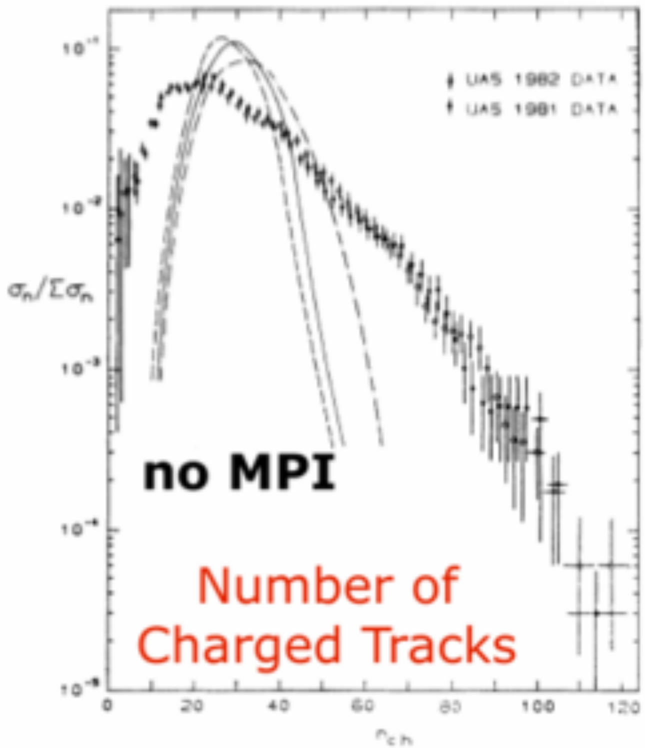


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

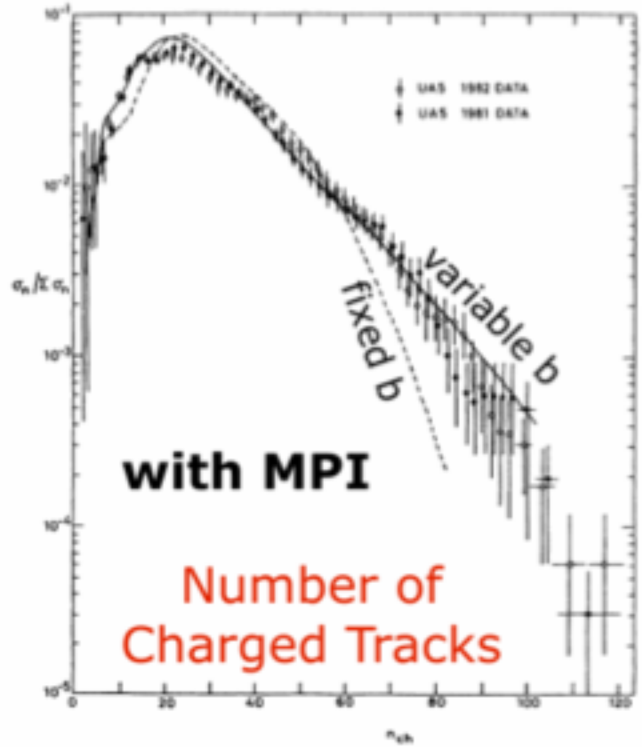
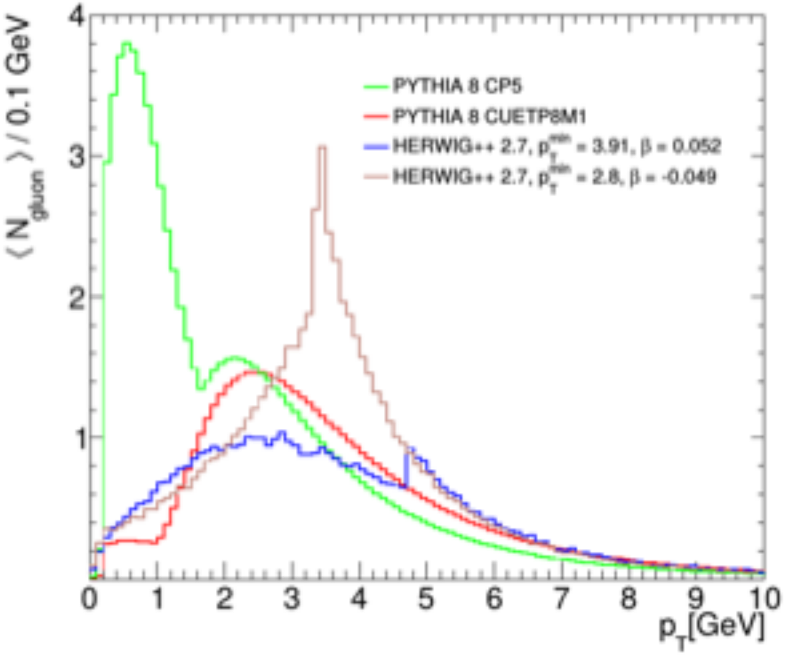


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

Sjöstrand & v. Zijl,
Phys.Rev.D36(1987)2019

Motivation. Data can help to improve the MPI models

Different MPI models have different assumptions, different parameter settings for example:

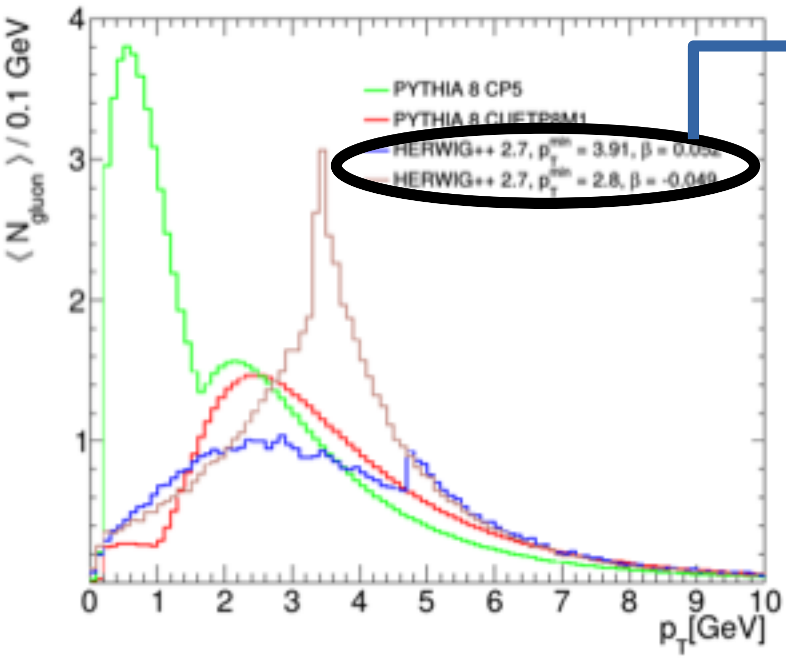


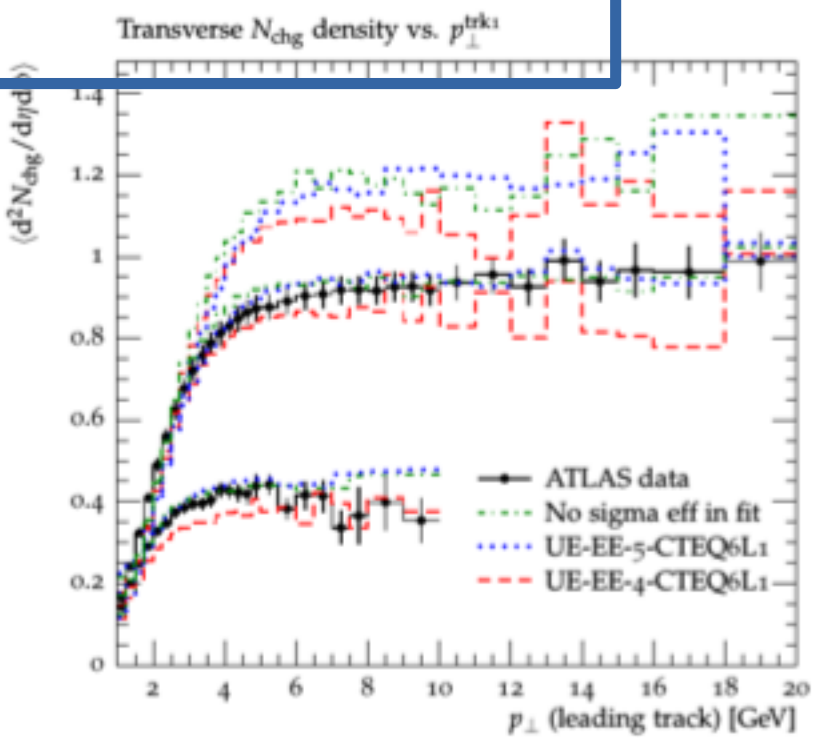
Extrapolation to non-perturbative region

Motivation. How do we know MPI exists?

Different MPI models have different assumptions, different parameter settings for example:

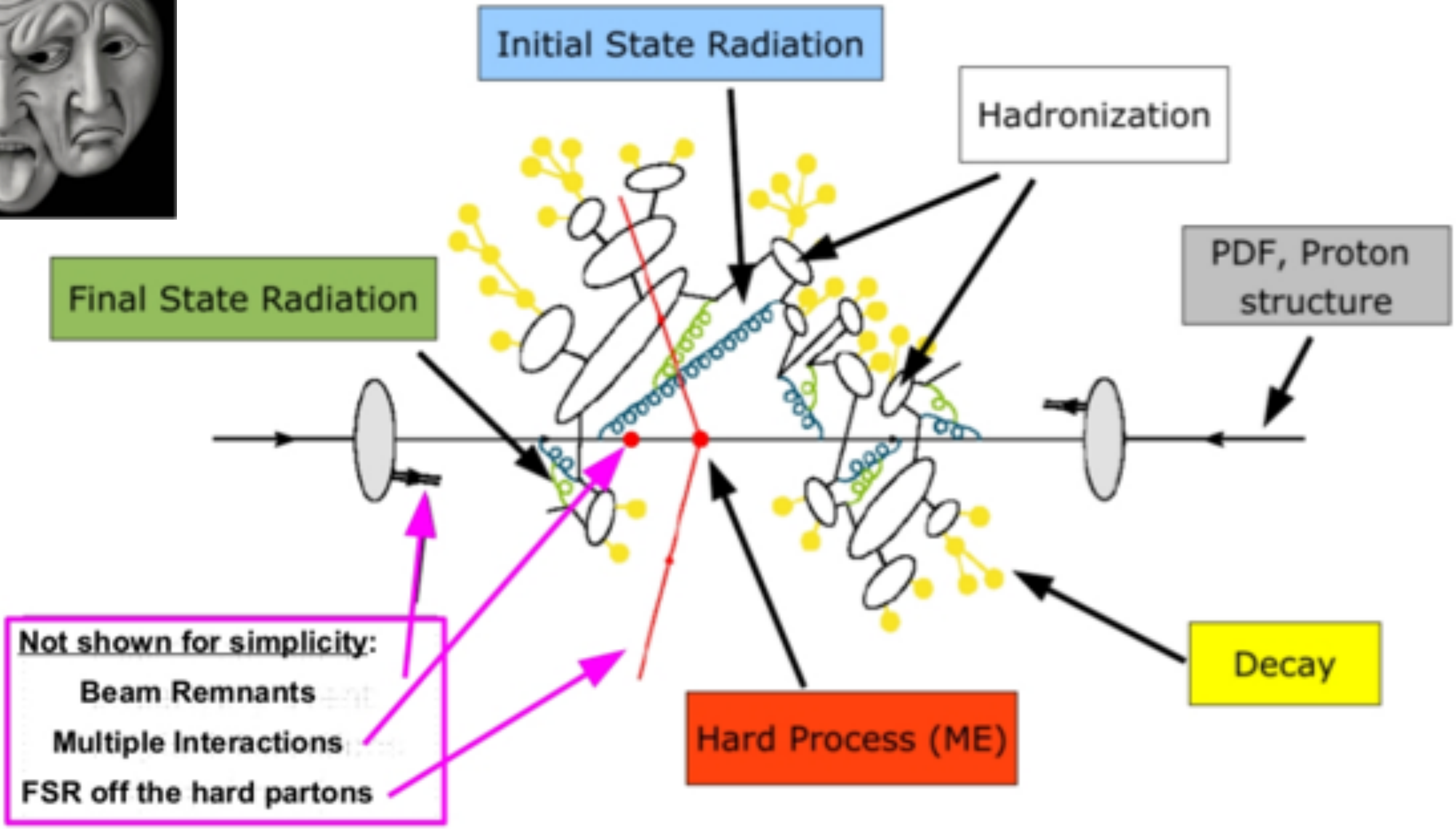
Similar predictions, for example two Herwig predictions below:
blue and green <=> blue and brown from left Fig.





Extrapolation to non-perturbative region

1.Monte Carlo Event Generators (all QCD faces)



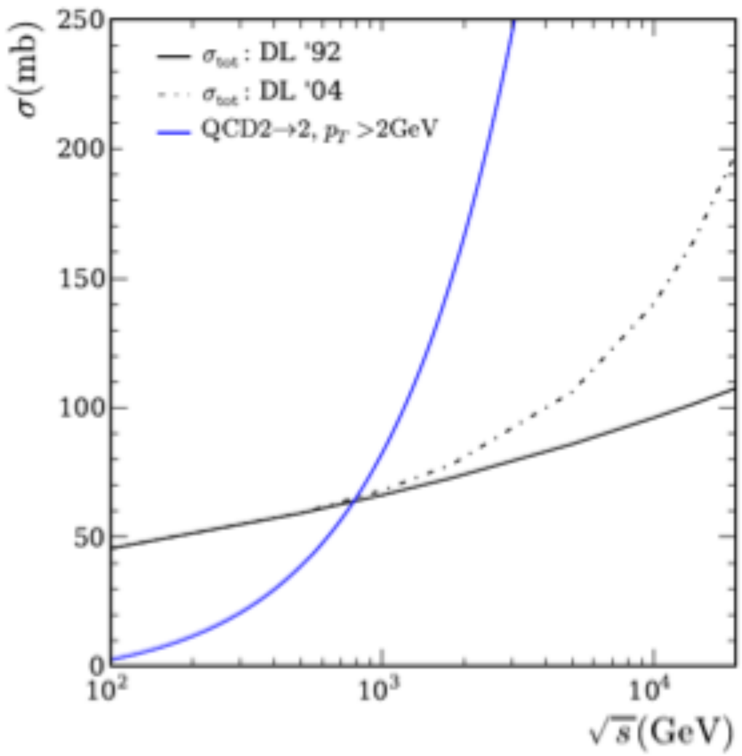
taken from Stefan Gieseke©

The general approach is the same in different programs but the models and approximations used are different.

1.MPI models in Monte Carlo Event Generators

Inclusive hard jet cross section in pQCD:

$$\sigma^{\text{inc}}(s, p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2)\, f_j(x_2, Q^2)\; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$



$\sigma^{\text{inc}} > \sigma_{\text{tot}}$ eventually

Interpretation:

- σ^{inc} counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\text{inc}} = \langle n_{\text{dijets}} \rangle \sigma_{\text{inel}}$$

MPI Eikonal model basics – Overlap function

Assumptions:

- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$\bar{n}(\vec{b},s) = L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|)$$

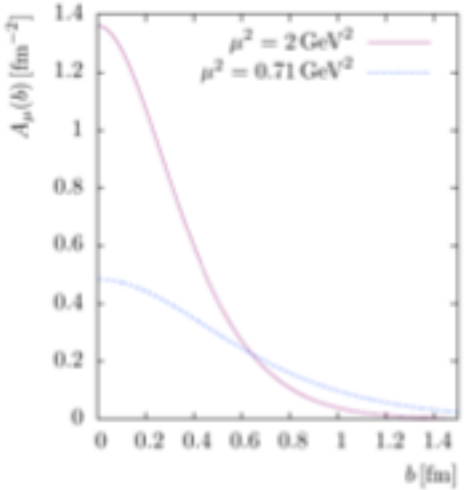
$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|)$$

$$= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\text{min}}) \,.$$

- at fixed impact parameter b, individual scatterings are independent (leads to the Poisson distribution)

MPI model in Herwig 7 – key components

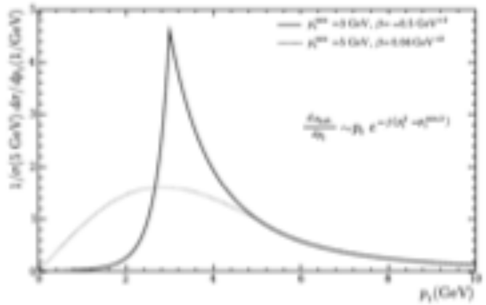
Matter distribution (μ^2)



Based on electromagnetic form factor

(radius of the proton free parameter)

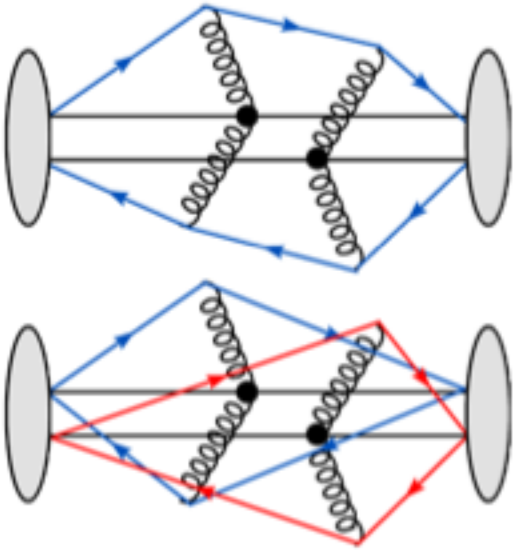
Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

Energy dependent $p_t^{\min}$

Colour structure (p_{reco}, p_{CD})



Possibility of change of color structure (color reconnection)

[Gieseke, Röhr, AS, EPJC 72 (2012)]

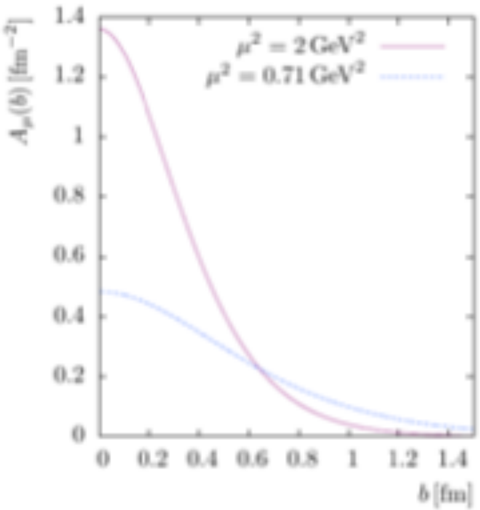
The least understood part of modeling

Main parameters:

- μ^2 - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components $\Rightarrow p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- p_{reco} - colour reconnection

MPI model in Herwig 7 – key components

Matter distribution (μ^2)



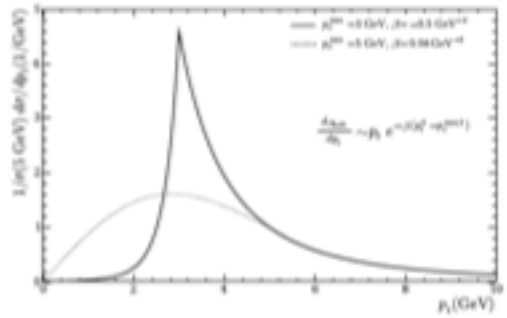
Based on electromagnetic form factor (radius of the proton free parameter)

Pythia:

- Many options including double Gaussian (similar shape to EE)

- x-depended overlap [Corke, Sjostrand, JHEP 1105:009]

Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

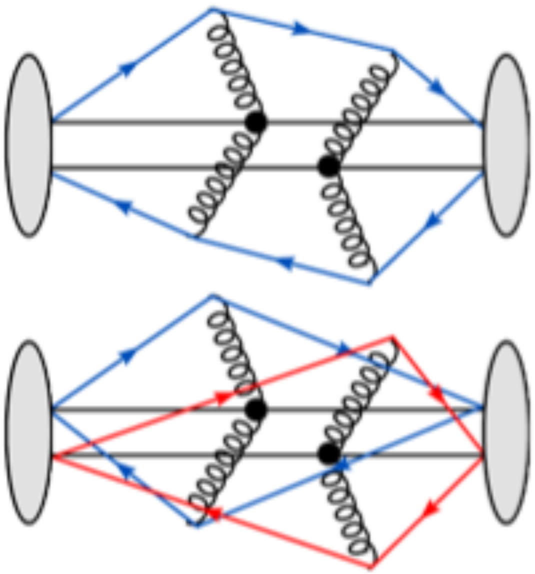
Energy dependent $p_t^{\min}$

Pythia:

Regularise cross section with $p_t^{\min}$ as free parameter:

$$\frac{d\sigma}{dp_T^2} \propto \frac{\alpha^2(p_T^2)}{p_T^4} \rightarrow \frac{\alpha^2(p_T^2 + p_t^{\min 2})}{(p_T^2 + p_t^{\min 2})^2}$$

Colour structure (p_{reco}, p_{CD})



Possibility of change of color structure (color reconnection)
[Gieseke, Röhr, AS, EPJC 72 (2012)]
The least understood part of modeling (very active area research)

Pythia:

The most recent development: String Formation Beyond Leading Colour J. Christiansen, P. Skands [arXiv:1505.01681] …

MPI model in Monte Carlo Generators

Herwig++ MPI model with independent hard and soft processes, showered and with colour reconnection. Just few parameters.

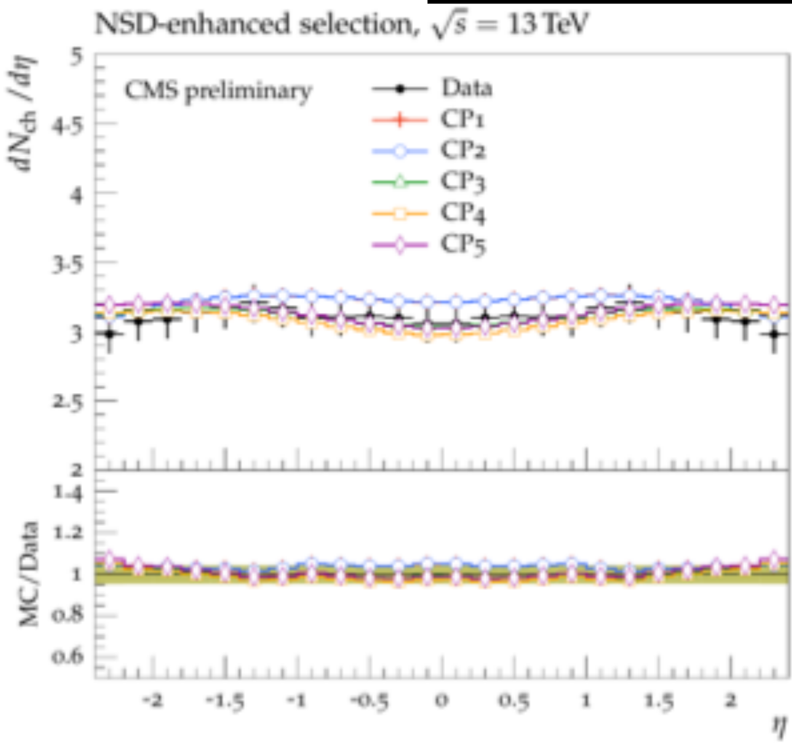
Pythia MPI interleaved with showering. MPI ordered in p_T. Many options and parameters (Pythia has strong emphasis on NP physics) $\Rightarrow$ many tune families.

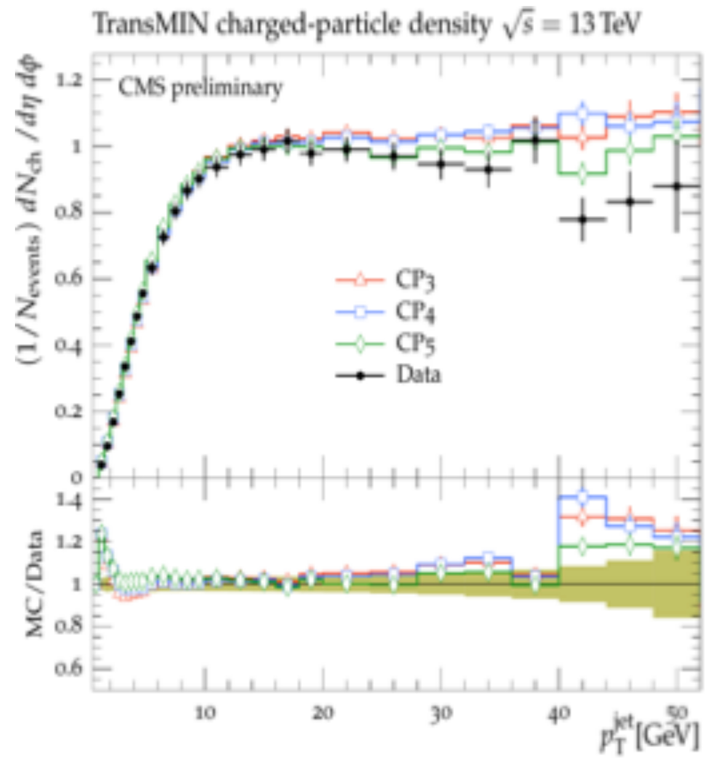
Sherpa New model - SHRiMPS with integrated diffraction based on KMR (Khoze-Martin-Ryskin model). Model in development

MC versions

- Pytnia 8: tunes CP2, CP4, CP5 (newest CMS tunes) and CUETP8M1
  (When I will show the results I will explain some differences between them)

<u>Similar description of both MB and UE data</u>





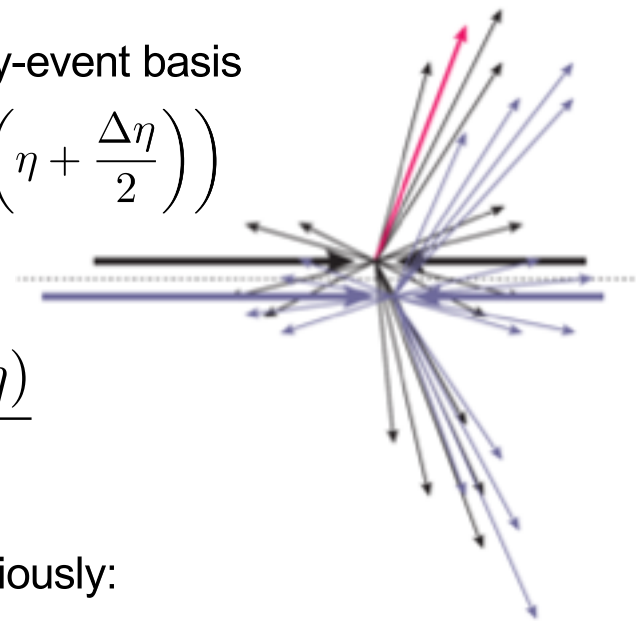
- Herwig++: two tunes both giving very good description of UE data over different s
- Sherpa: only one tune exists (many parameters, not so good description of MB/UE data)

Mini jet correlations: we suggest to measure how the transverse momenta of hadrons produced in association with a trigger object are balanced as a function of rapidity.

1. We pick a trigger object (particle, jet) within a fixed rapidity interval and a certain small pT.

2. Calculate pT recoil as a function of rapidity on the event-by-event basis

$$p_T^{\mathrm{rec}\,(k)}(\eta) = \sum_{i=1,\dots n,\, i\neq k} |\vec{p}_{Ti}| \cos\phi_i \; \Theta\left(\left(\eta - \frac{\Delta\eta}{2}\right) < \eta_i < \left(\eta + \frac{\Delta\eta}{2}\right)\right)$$



3. The average over N events:

$$\langle p_T^{\mathrm{rec}} \rangle (\eta) = \frac{\sum_{k=1}^{N} p_T^{\mathrm{rec}\,(k)}(\eta)}{N}$$

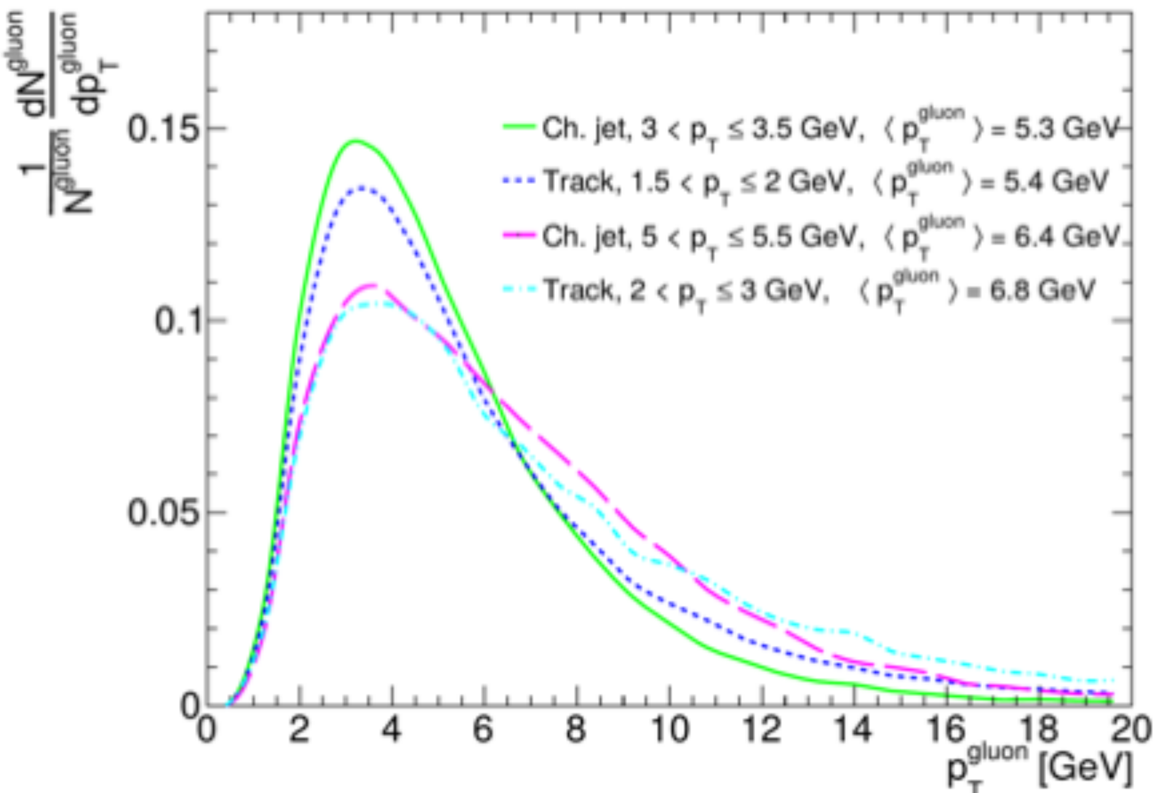
The total momentum conservation requirement gives, obviously:

$$\int d\eta \, \langle p_T^{\mathrm{rec}} \rangle (\eta) = \int d\eta \, \left\langle p_T^{\mathrm{trig}} \right\rangle (\eta)$$

Suggested variable (a) suppresses contribution of MPI, (b) nonperturbative correlations die out exponentially with Δη, pQCD correlations are much wider.

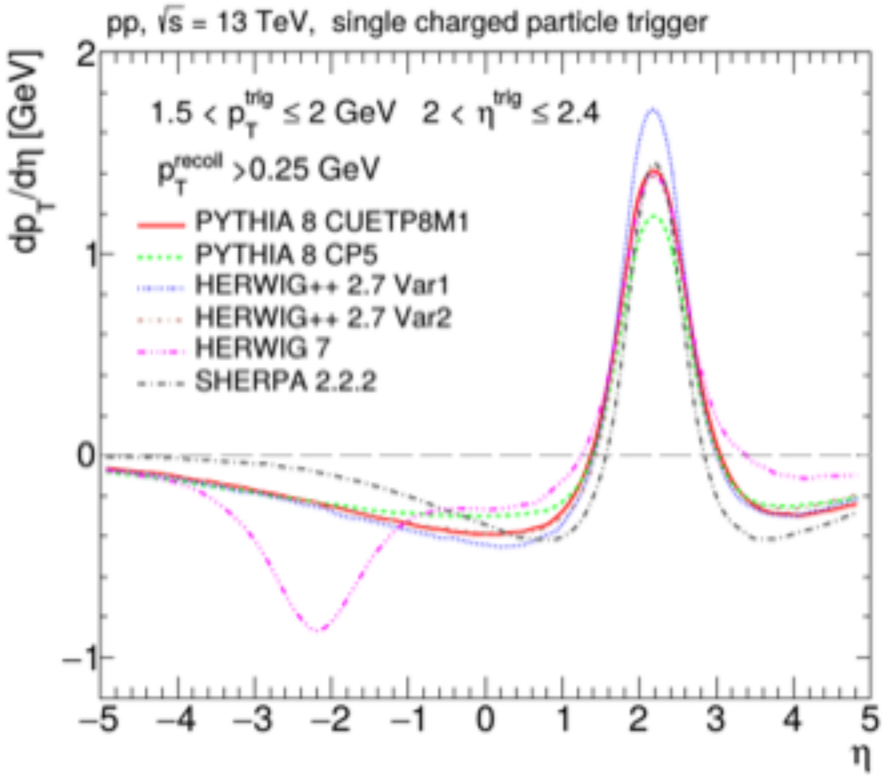
We consider realistic experimental situation suitable for ATLAS/CMS:

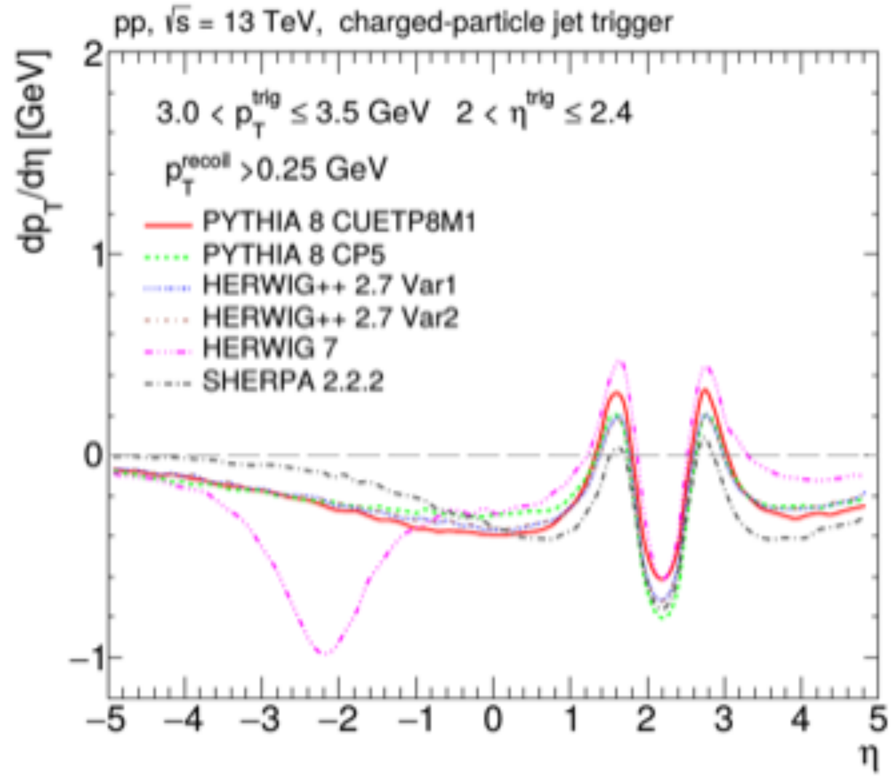
- Charged particles with $\eta < 2.4$ and $p_T > 250$ MeV
- Two trigger objects the both within $2.0 < \eta^{trig} < 2.4$:



1. single charged particle $1.5 < p_T^{trig} < 2.0$ GeV
2. charged-particle jet ($R = 0.4$ in the anti-k_T) $3.0 < p_T^{trig} < 3.5$ GeV

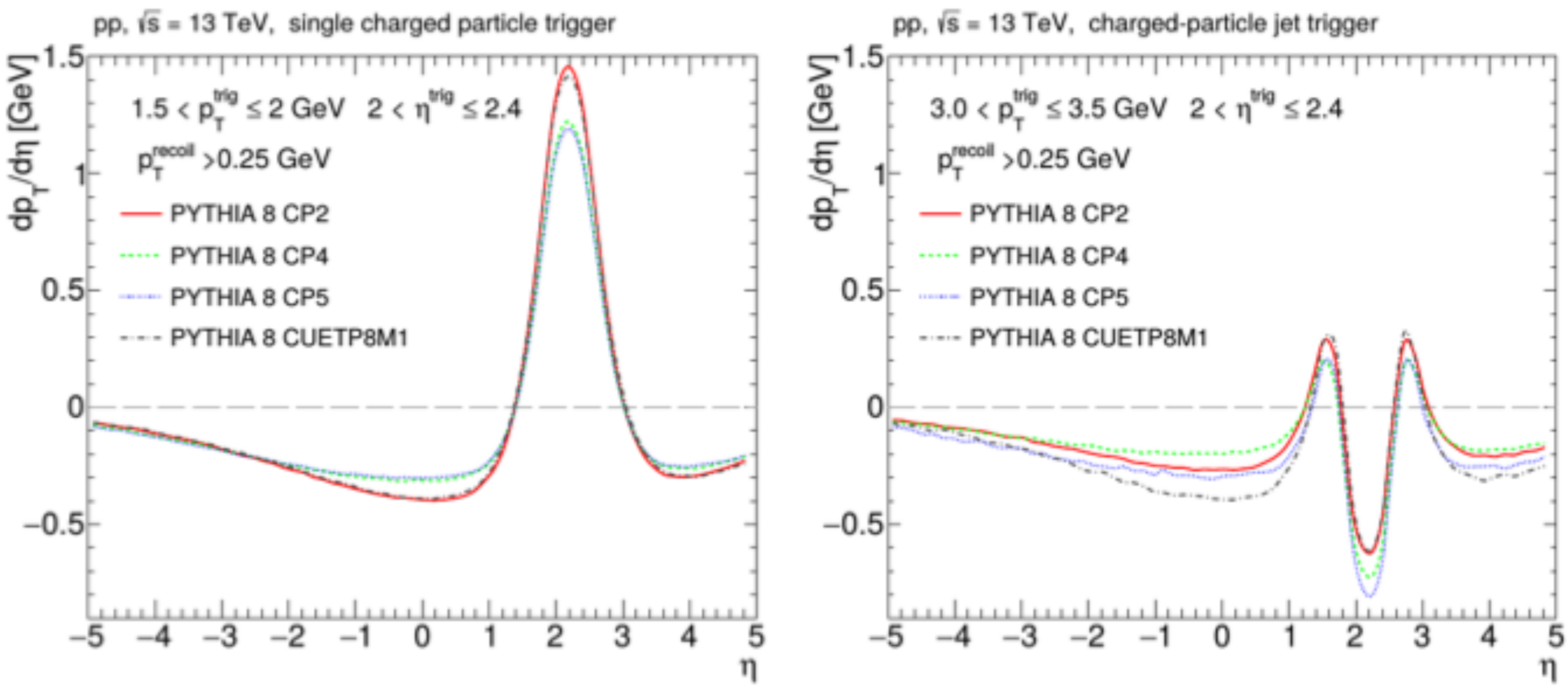
Results at 13 TeV





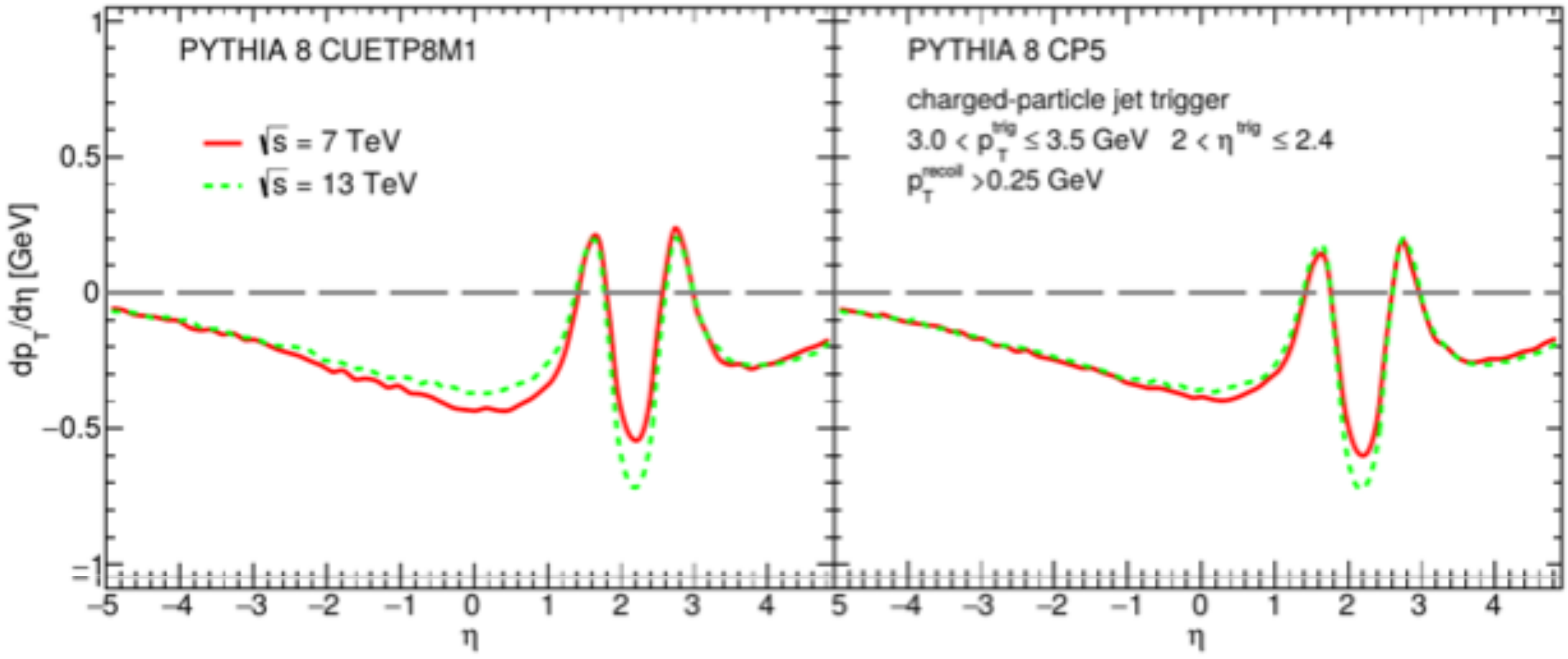
- We see that for the both trigger objects we see quite different predictions
- Charge trigger particle: we see strong correlation of particles around the trigger due to parton shower (soft-collinear) radiation around the trigger.
- Jet trigger: we see a dale since we remove the trigger (jet’s particles)

Results at 13 TeV: Pythia tunes



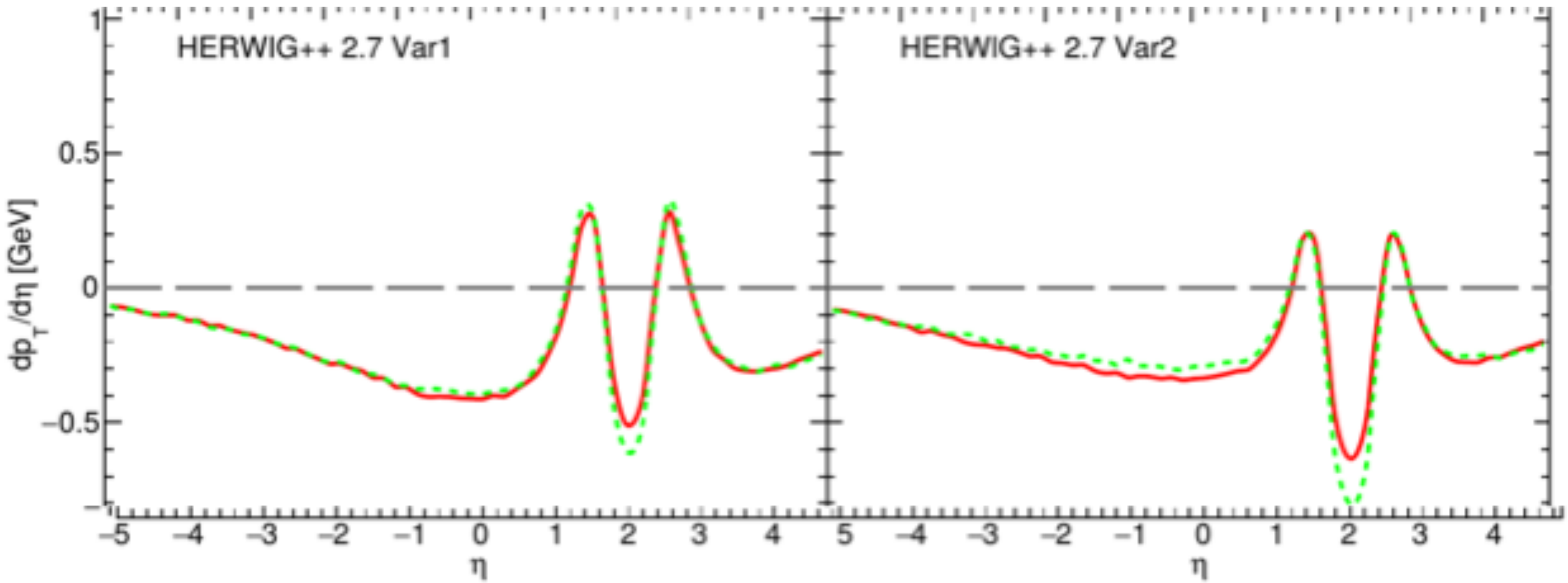
- Charge particle trigger: clearly divides two tunes into two groups (CP2, CUETP8M1) and (CP4, CP5) the main difference between them is usage of LO and NNLO PDF (low gluon x)
- Jet trigger: offers an additional separation power.

Results energy dependence 7 and 13 TeV: Pythia



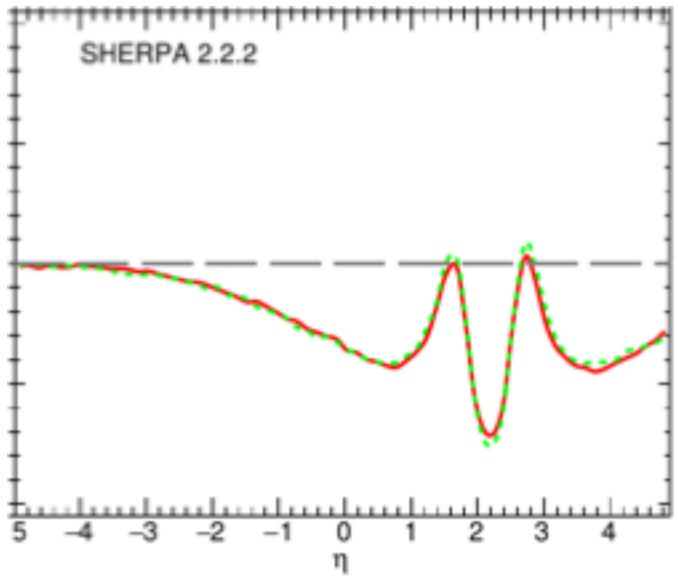
- Stronger energy dependence in the case of CUETP8M1 (b=0.252) then CP5 (b= 0.033 – almost flat!)
  - $p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- The rest of energy dependence is govern by LO vs NNLO pdf effects

Results energy dependence 7 and 13 TeV: Herwig++



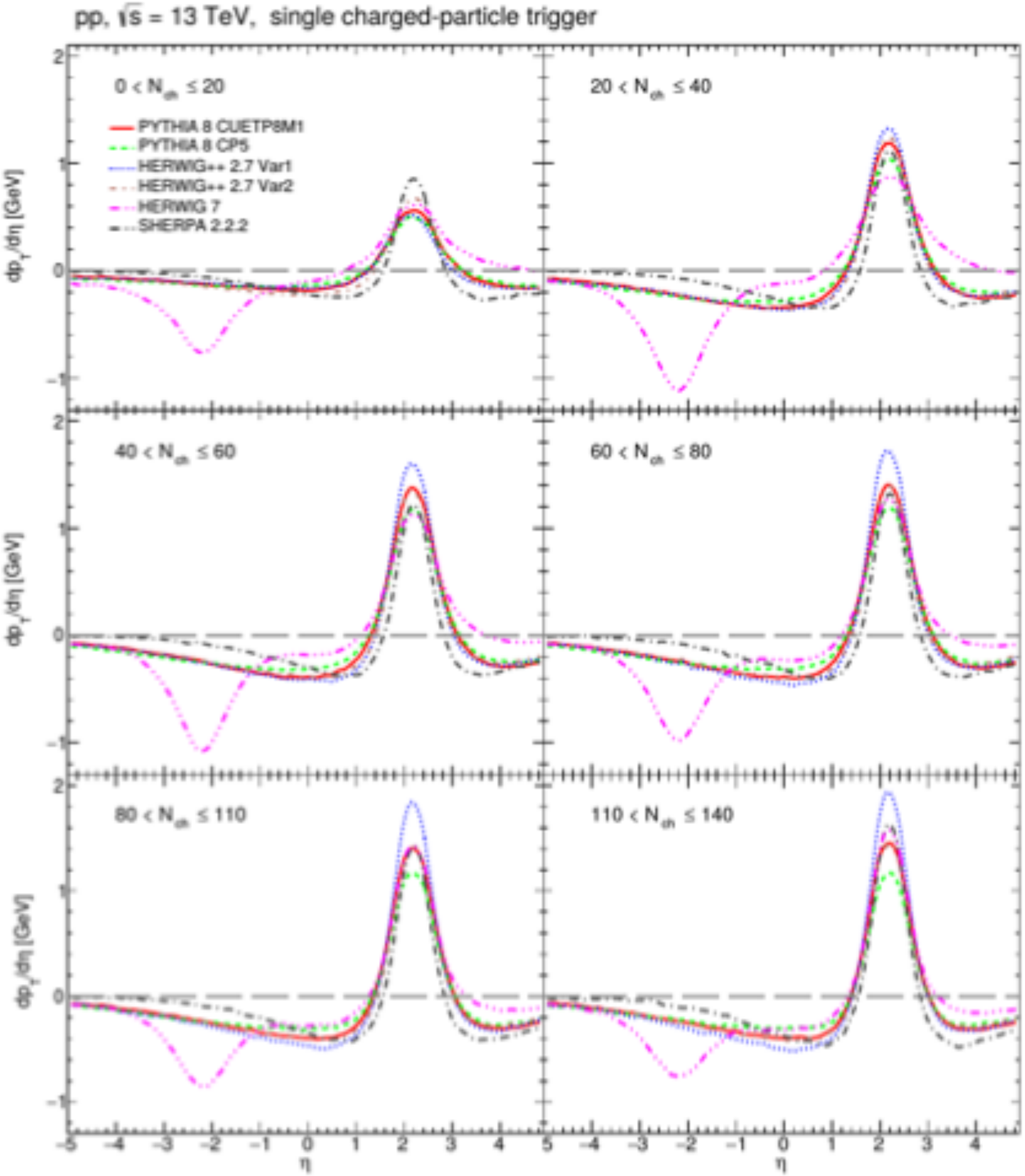
- Stronger energy dependence in the case of Var1 (ptmin~4GeV) then var2 (ptmin~3GeV)
- Ptmin is the transition to soft MPI which is not showered, for Var1 more soft MPI (less particles in a jet smaller dale)

Results energy dependence 7 and 13 TeV: Sherpa



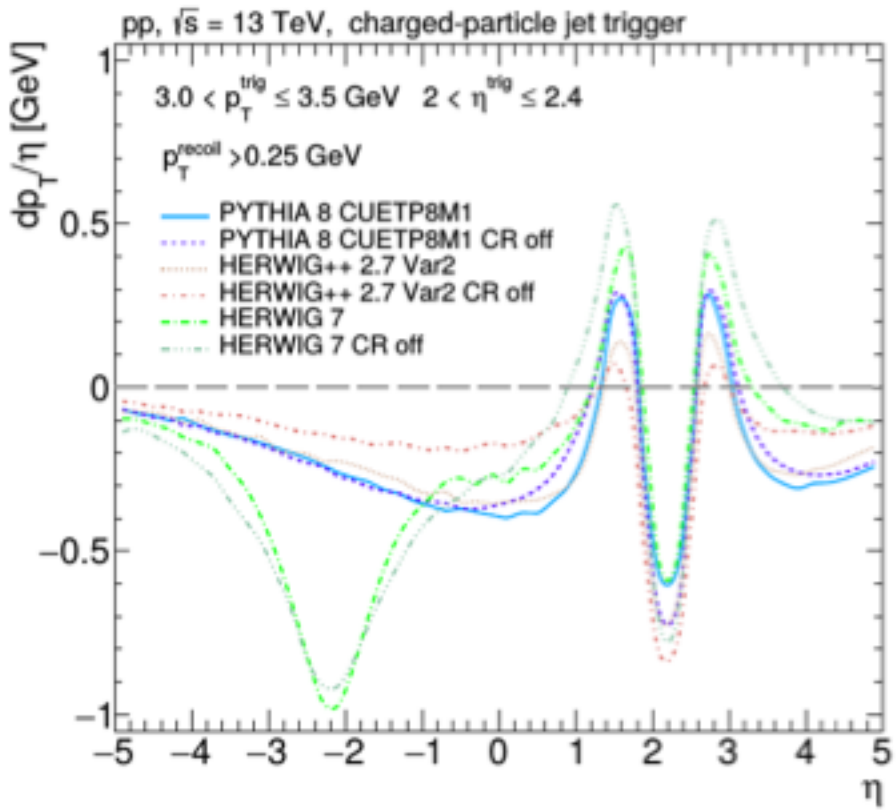
- No energy dependence – easy to check by a measurement!

Results multiplicity dependence at 13 TeV



- We use charged track since for high multiplicity charged jet would
- be "populated" by UE contribution (half of jet energy at nch=100 would be from UE).
- Pythia and Herwig fast increase of the rapidity correlation up to Nch=60 then saturates
- Sherpa continuous increase of the peak along the trigger direction
- Two Herwig predictions could be explain by different transverse proton structure. Peak along trigger higher for lower sigma_eff.

Results colour reconnection effects



- Some sensitivity especially in Herwig

Summary and outlook

- We have introduced a new observable which probes interplay between the soft and hard physics at moderate pT via probing long and short range rapidity correlations of transverse momenta of charged particles/minijets.

- We show that the observable is sensitive to basic mechanisms and components used in the present MC models, such as a suppression of low-pT jet production, parton distribution functions, a transverse geometry of proton, a color reconnection mechanism, and their evolution with collision energy.

-
- Outlook:
  - - measure it! :)
  - - it would be also interesting to study such correlations in pA and AA
  - - extended the method by using as trigger particles two hadrons with a given azimuthal angle difference.

Thank you for your attention!

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-
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Hard matrix element LO