# Studying Minijets and Multiple Particle Interactions with Rapidity Correlations

Andrzej Siódmok
in collaboration with M. Azarkin, P. Kotko, and M. Strikman
based on EPJC 79 (2019) no.3, 180

NARODOWE CENTRUM NAUKI

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

MCnet

QCD@2019, 15-19 July 2019, Buffalo US

NCN, Poland Grant No. 2016/23/D/ST2/02605

THE BUFFALO NEWS

# Snowfall in Siberia may offer a hint of what's coming this winter


*One MIT researcher has found a correlation between October snowfall in Siberia and the pattern taken by the polar jet stream, which could help predict what winters will look*

# Outline

1. Motivation

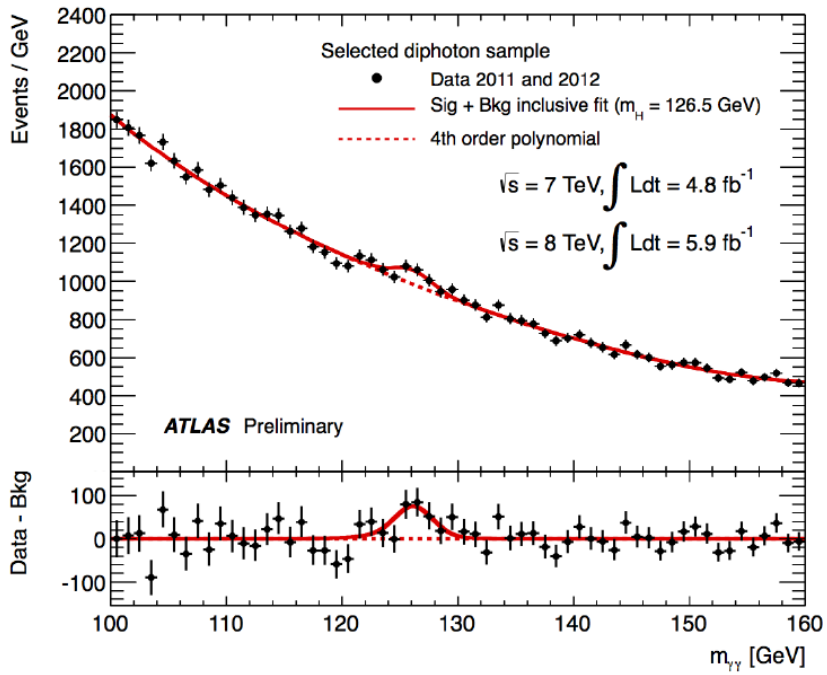
2. Multiple Particle Interactions (MPI) models in Monte Carlo Event Generators

3. New observable to study rapidity correlation of minijets

4. Summary and outlook

# Motivation – Monte Carlo Event Generators

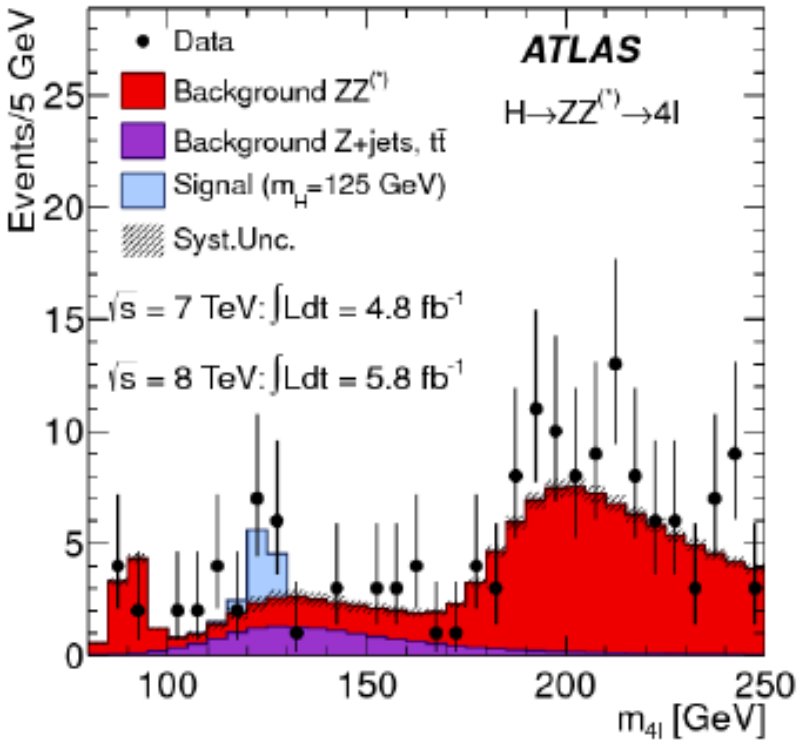
The predictions were heavily used for the **design of existing experiments ATLAS, CMS, LHCb.** The programs are used to **devise new strategies for analyses**, and for the **interpretation of data**.




**[Liron BARAK's talk]**

# Motivation – Monte Carlo Event Generators

The predictions were heavily used for the **design of existing experiments ATLAS, CMS, LHCb.** The programs are used to **devise new strategies for analyses**, and for the **interpretation of data**.




**Last Tuesday Pythia 6 manual reached 10000 citations!**
**[JHEP 0605 (2006) 026]**

MCEG are cited by most papers from LHC experiments:

Published papers by ATLAS, CMS, LHCb: **2252**
Citing MCnet projects: **1888 (84%)**

The remaining 16% of the papers cite indirectly, are hard-ware specific papers, or CMS/LHCb or are 'short of space' for listing all references.

# Complex structure of Quantum Chromodynamics – three faces of QCD

Perturbative: $\alpha_s \ll 1$

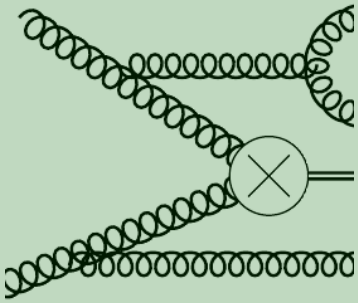
$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \alpha_s^3 \sigma_3 \ldots$$

$$\sigma_0 > \alpha_s \sigma_1 > \alpha_s^2 \sigma_2 > \alpha_s^3 \sigma_3 \ldots$$

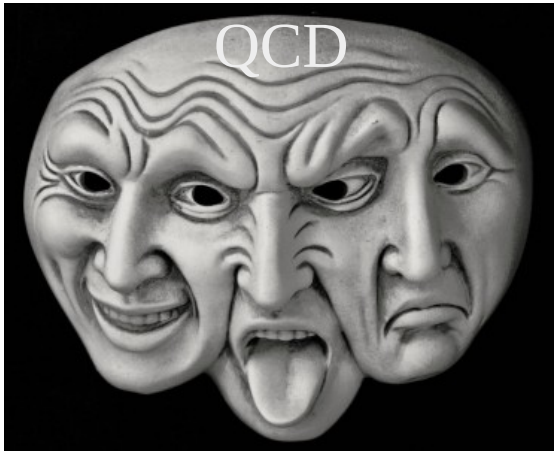
LO NLO NNLO N3LO

State of the art:

*"Higgs boson gluon-fusion production in N3LO QCD"* *Phys. Rev. Lett. 114, 212001 (2015)*



Example of one of hundreds of diagram



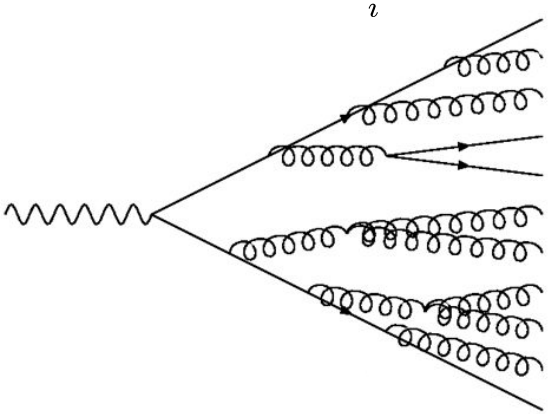

Perturbative resummation:

- enhanced terms

$$\sigma_i \supset L^i$$

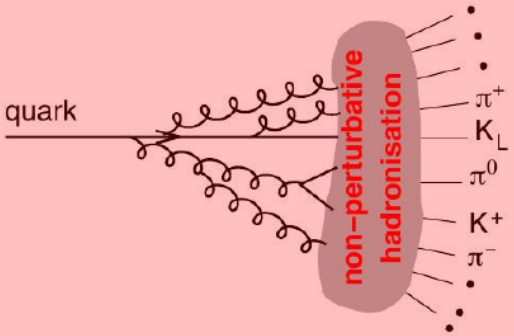
$$\sigma_0 \sim \alpha_s L \sim \alpha_s^2 L^2 \sim \alpha_s^3 L^3 \ldots$$

- Resum them $\sum_i^\infty \alpha_s^i L^i$



Non-Perturbative: $\alpha_s \gg 1$

- Perturbative techniques break down
- Non-pertubative models inspired by physical motivations and **data**
- Lattice QCD?



# Motivation - Is MPI important?

**[Massimiliano GRAZZINI's talk]**

- Better control of perturbative corrections, and especially the so called "NLO revolution" leads to the situation in which more often the precision of the LHC measurements is limited by GPMC's non-perturbative components, such as multiparton interactions:

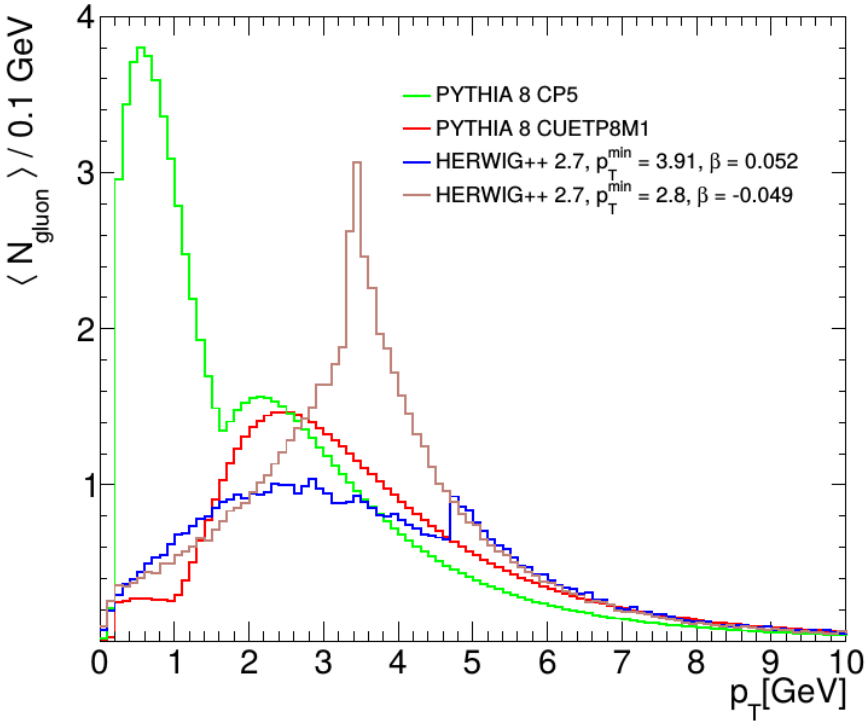
  - the top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]
  - W mass measurement using a new method [Freytsis at al. JHEP 1902 (2019) 003]
  - extraction of the strong coupling in [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5, 054013].

- MPI at the LHC give rise to different effects, among others a substantial increase of the unavoidable background to most observables (basically all which are based on jets) used for BSM physics

- HL LHC - we expect more pile up events – similar soft physics to MPI

# Motivation. Data can help to improve the MPI models

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

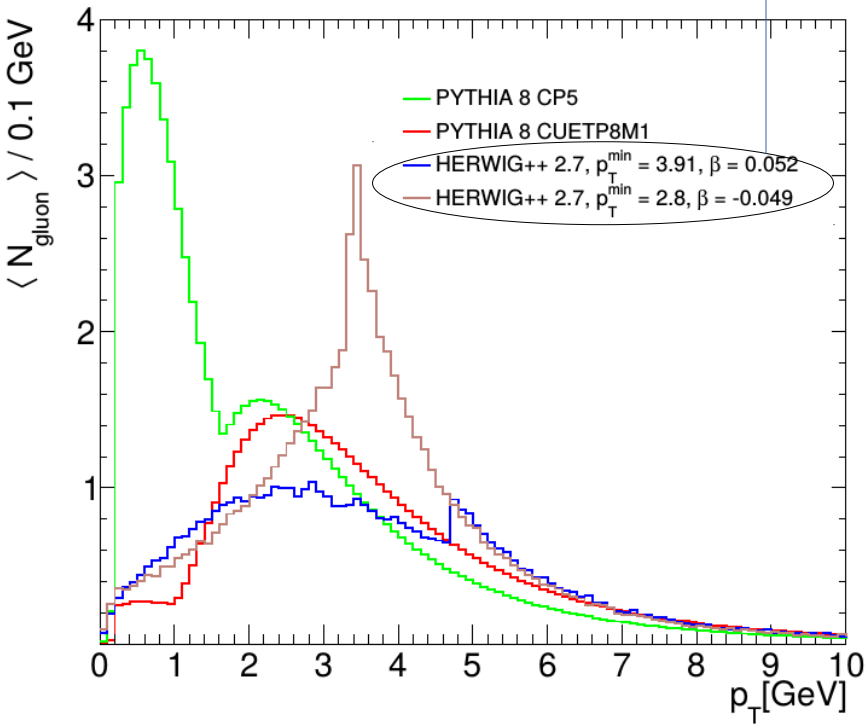



Extrapolation to non-perturbative region

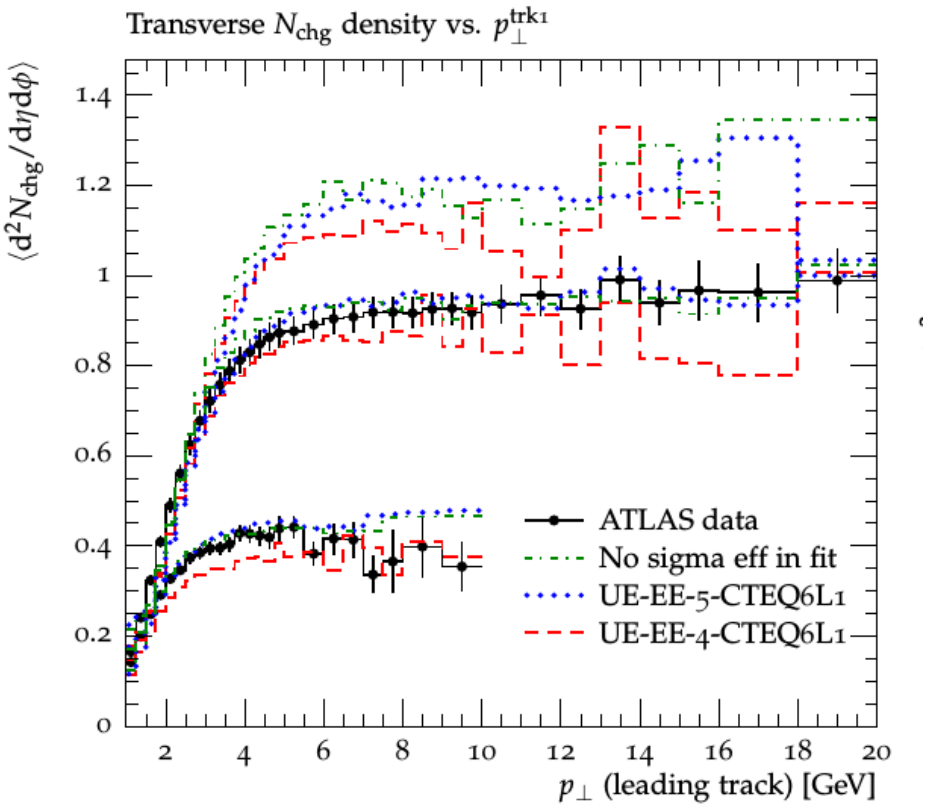
# Motivation. Data can help to improve the MPI models

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.

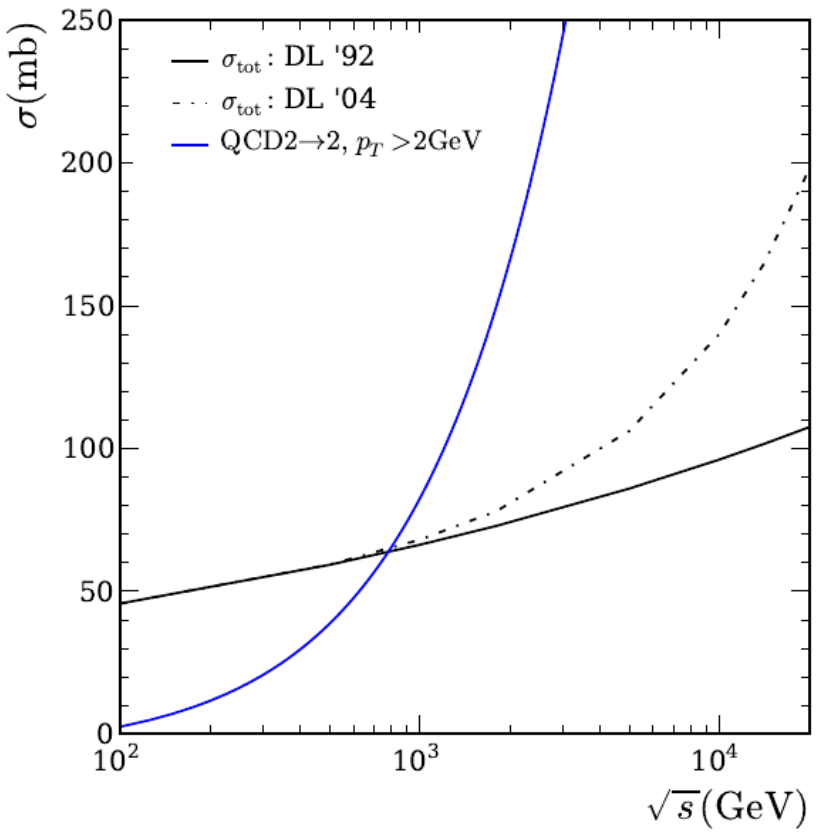



Extrapolation to non-perturbative region



Inclusive hard jet cross section in pQCD:

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




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

Interpretation:

- $\sigma^{\text{inc}}$ 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:

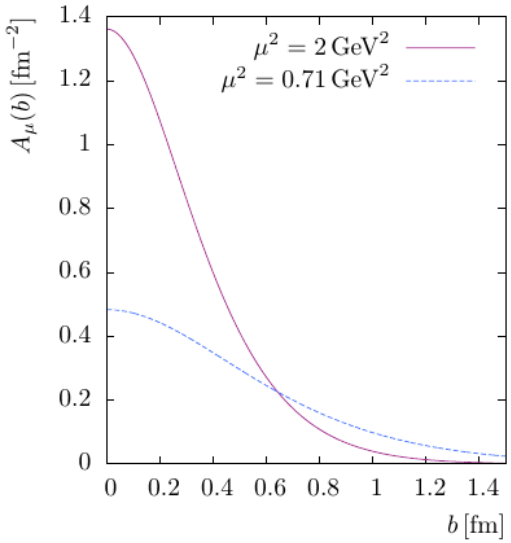
- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$
\begin{aligned}
\bar{n}(\vec{b}, s) &= L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|) \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\min}) \,.
\end{aligned}
$$

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

# MPI model in Herwig 7 – key components

Matter distribution ($\mu^2$)

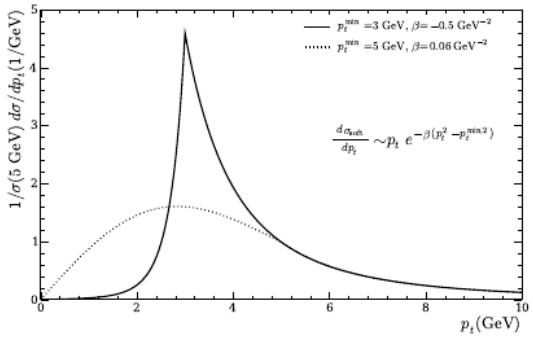



Based on electromagnetic form factor

(radius of the proton free parameter)

Extension to soft MPI

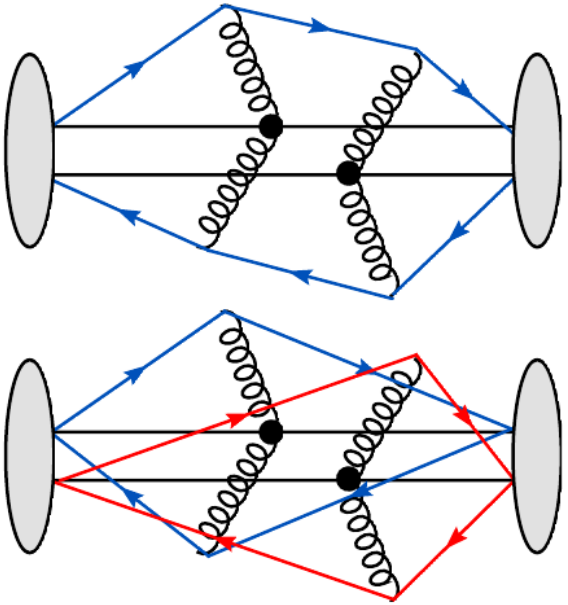
($p_t < p_t^{\min}$)




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)]

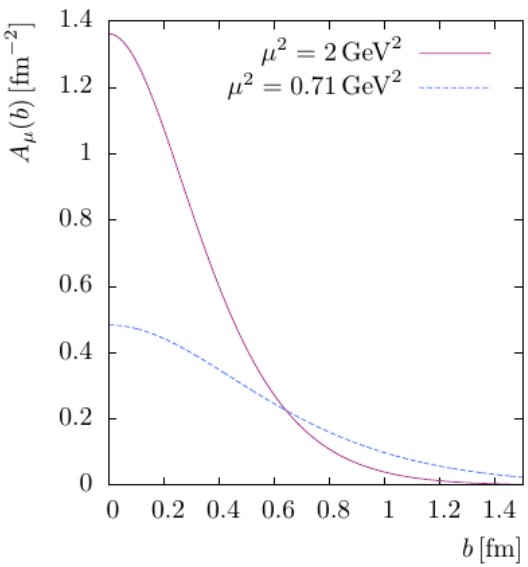
The least understood part of modeling

## Main parameters:

- $\mu^2$ - 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 ($\mu^2$)



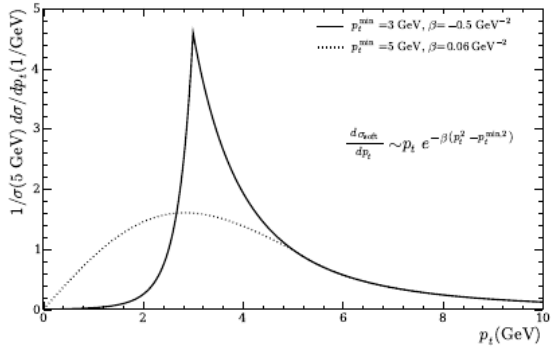

Based on electromagnetic form factor (radius of the proton free parameter)

**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 $p_t^{\min}$

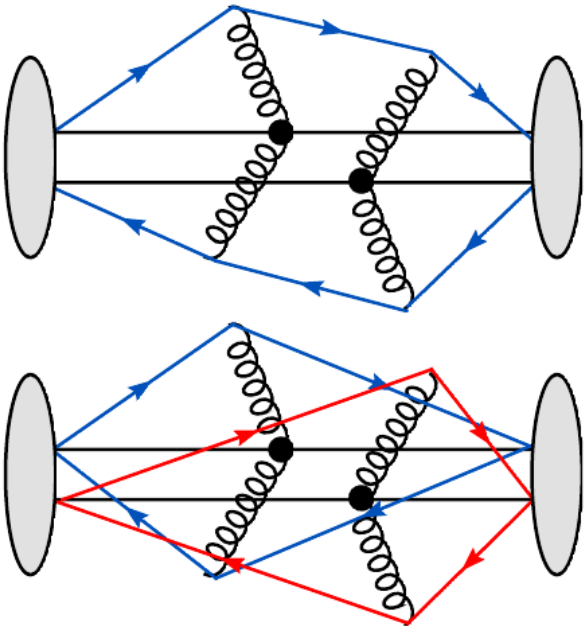
Energy dependent $p_t^{\min}$

**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.

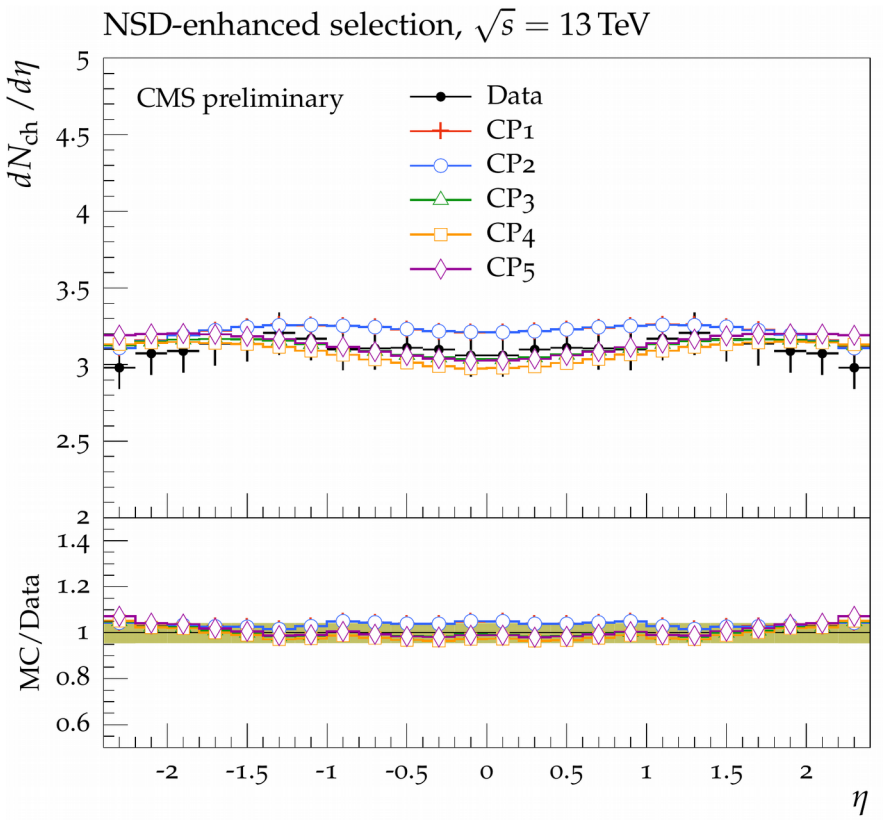
**Pythia** MPI interleaved with showering. MPI ordered in $p_T$. Many options and parameters (Pythia has strong emphasis on NP physics) $\Rightarrow$ many tune families.

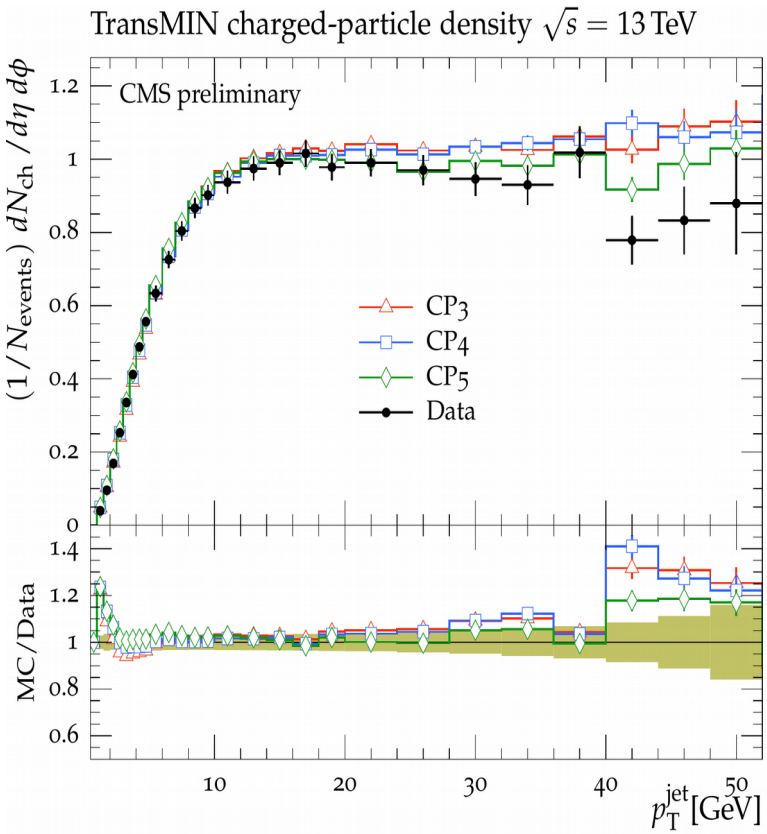
**Sherpa** New model - SHRiMPS with integrated diffraction based on KMR (Khoze-Martin-Ryskin model). Model in development

# 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 and also new soft model in Herwig 7
- Sherpa: only one tune exists (many parameters, not so good description of MB/UE data)

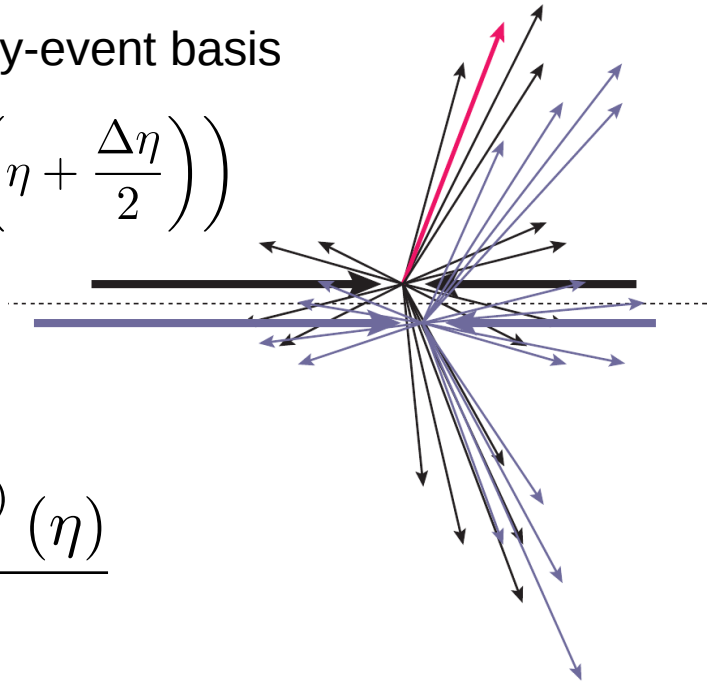
# The observable

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

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



3. The average over N events:

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

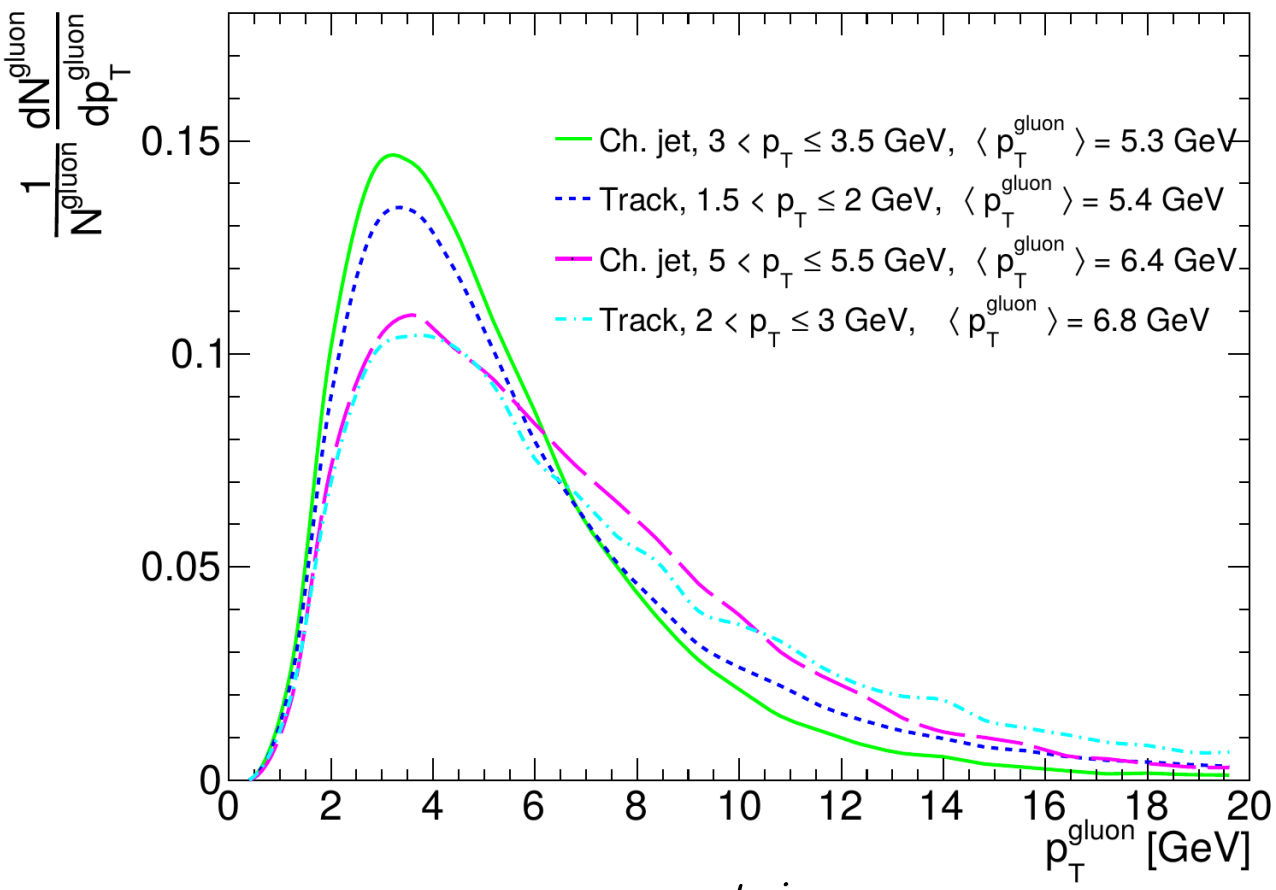
The total momentum conservation requirement gives, obviously:

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

# The observable and cuts

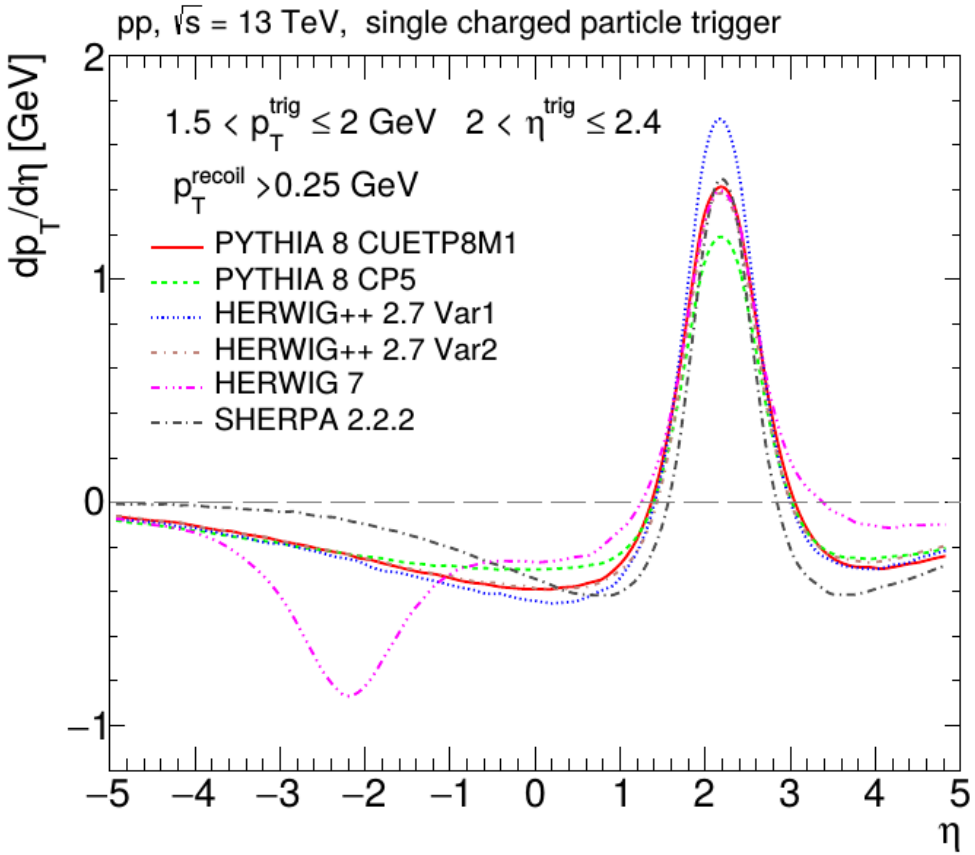
We consider realistic experimental situation suitable for ATLAS/CMS:

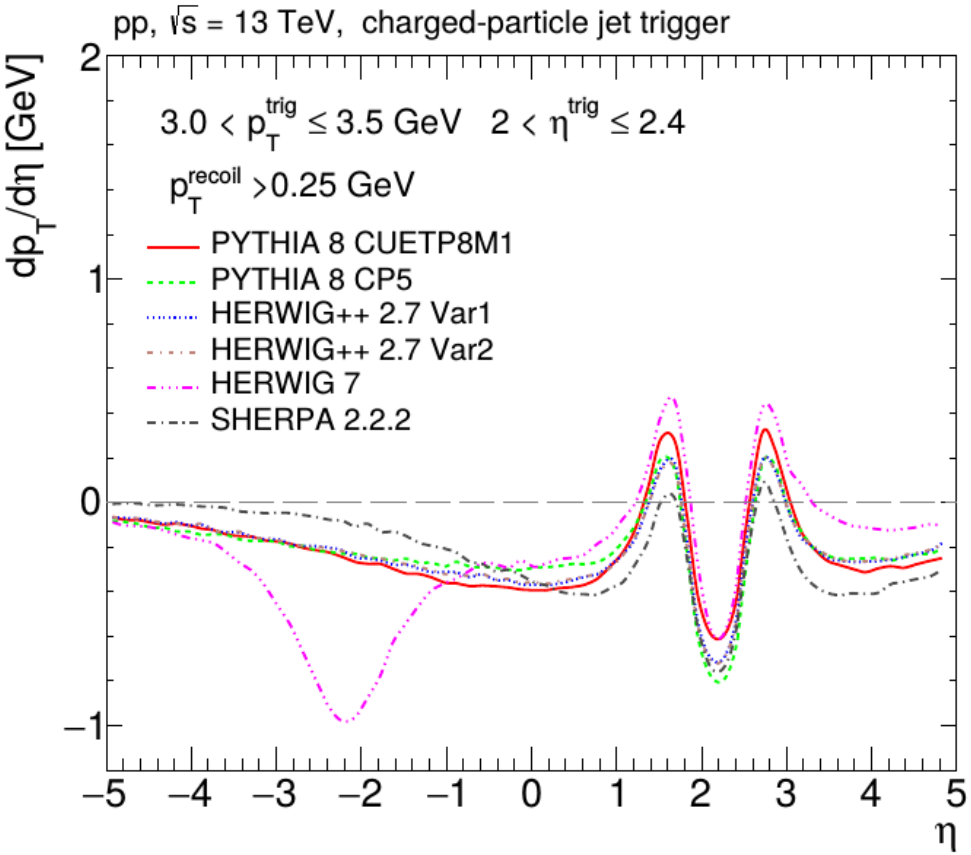
- Charged particles with $\eta < 2.4$ and $p_{\mathrm{T}} > 250$ MeV
- Two trigger objects the both within $2.0 < \eta^{trig} < 2.4$:




1. single charged particle $1.5 < p_{\mathrm{T}}^{trig} < 2.0$ GeV
2. charged-particle jet ($R = 0.4$ in the anti-$k_{\mathrm{T}}$) $3.0 < p_{\mathrm{T}}^{trig} < 3.5$ GeV

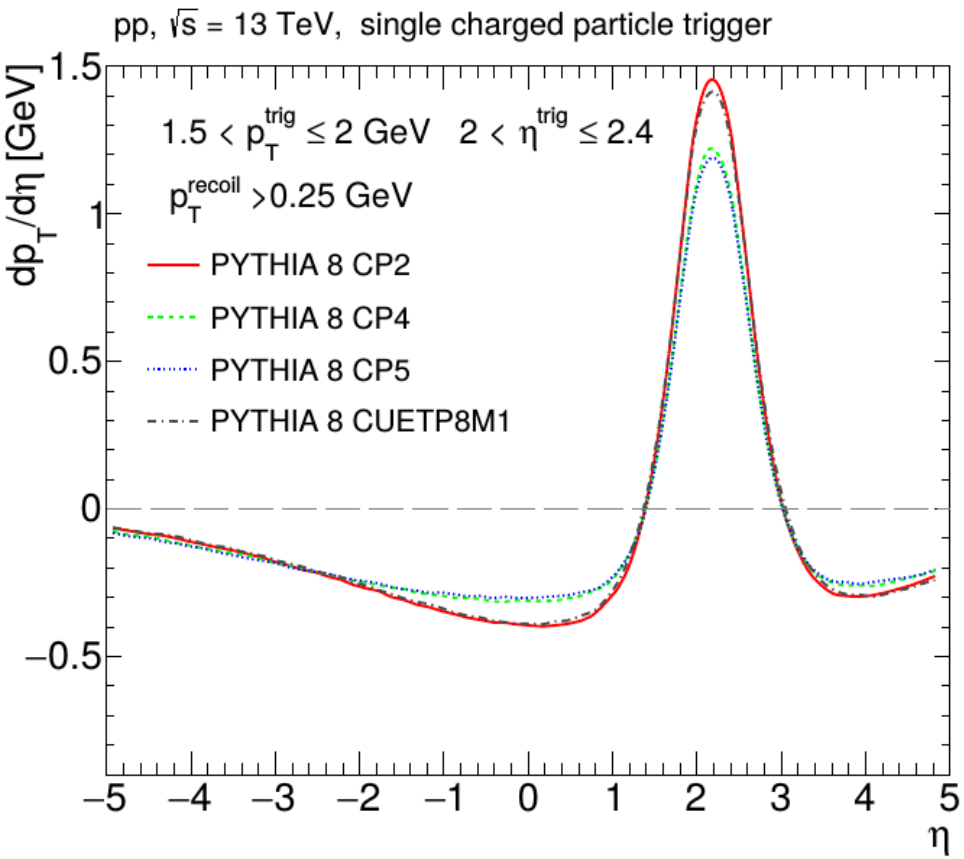
# Results at 13 TeV

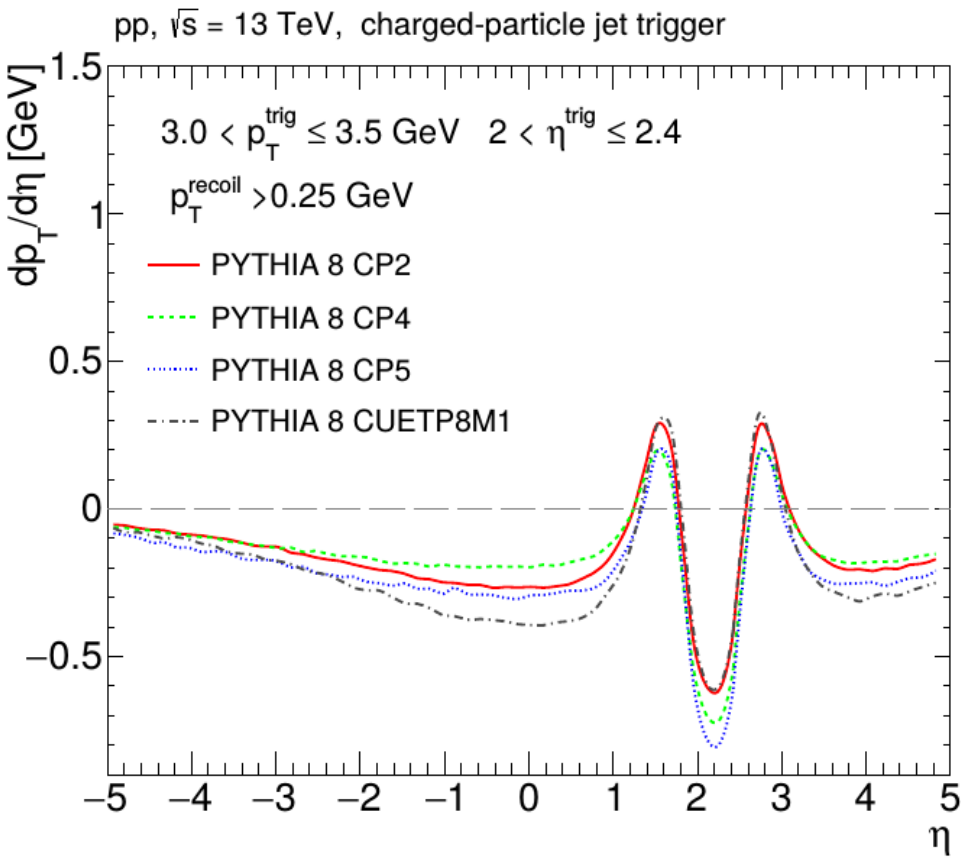



- We see that for the both trigger objects we see quite different predictions
- Charge trigger particle: we see strong correlation of particles around the trigger due to parton shower (soft-collinear) radiation around the trigger.
- Jet trigger: we see a dale since we remove the trigger (jet's particles)

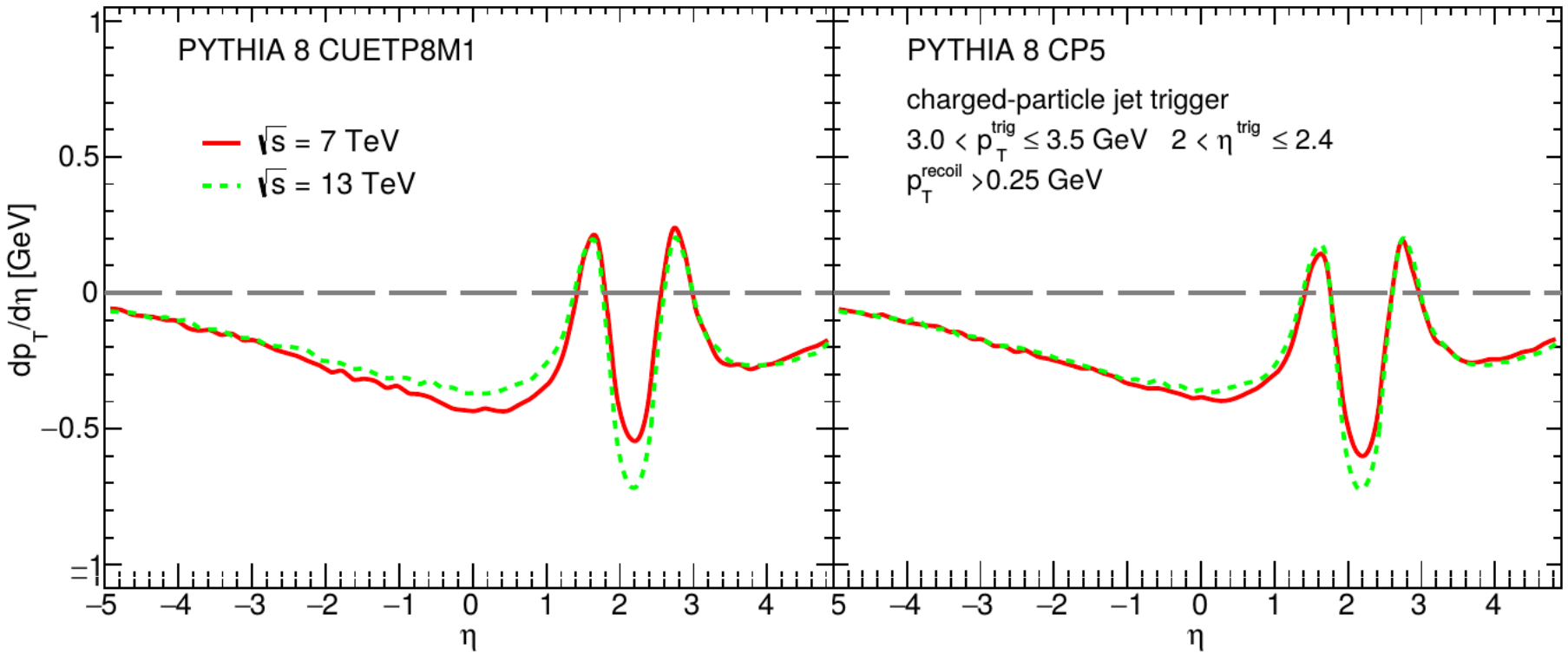
# Results at 13 TeV: Pythia tunes




- 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

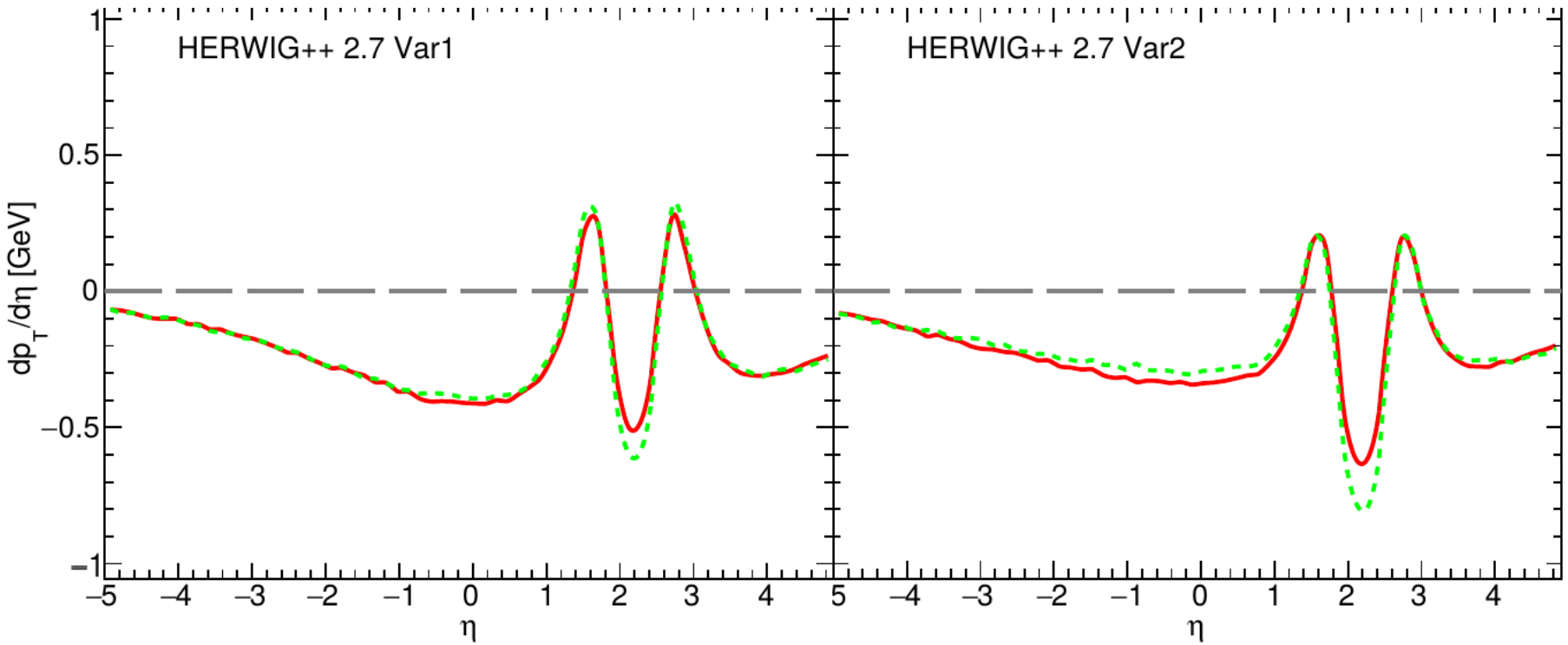



- Stronger energy dependence in the case of CUETP8M1 (b=0.252) then CP5 (b= 0.033 – almost flat!)

$$\cdot\ p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$$

- The rest of energy dependence is govern by LO vs NNLO pdf effects

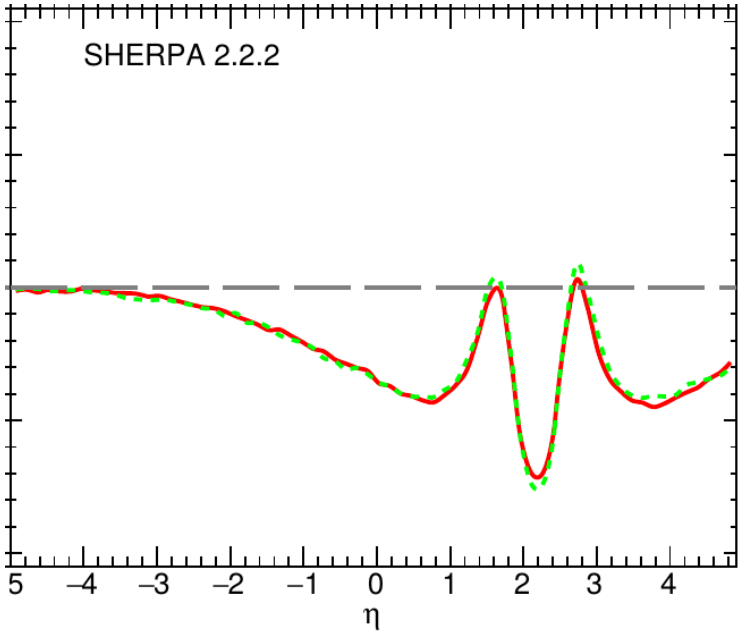
# Results energy dependence 7 and 13 TeV: Herwig++




- Stronger energy dependence in the case of Var1 (ptmin~4GeV) then var2 (ptmin~3GeV)

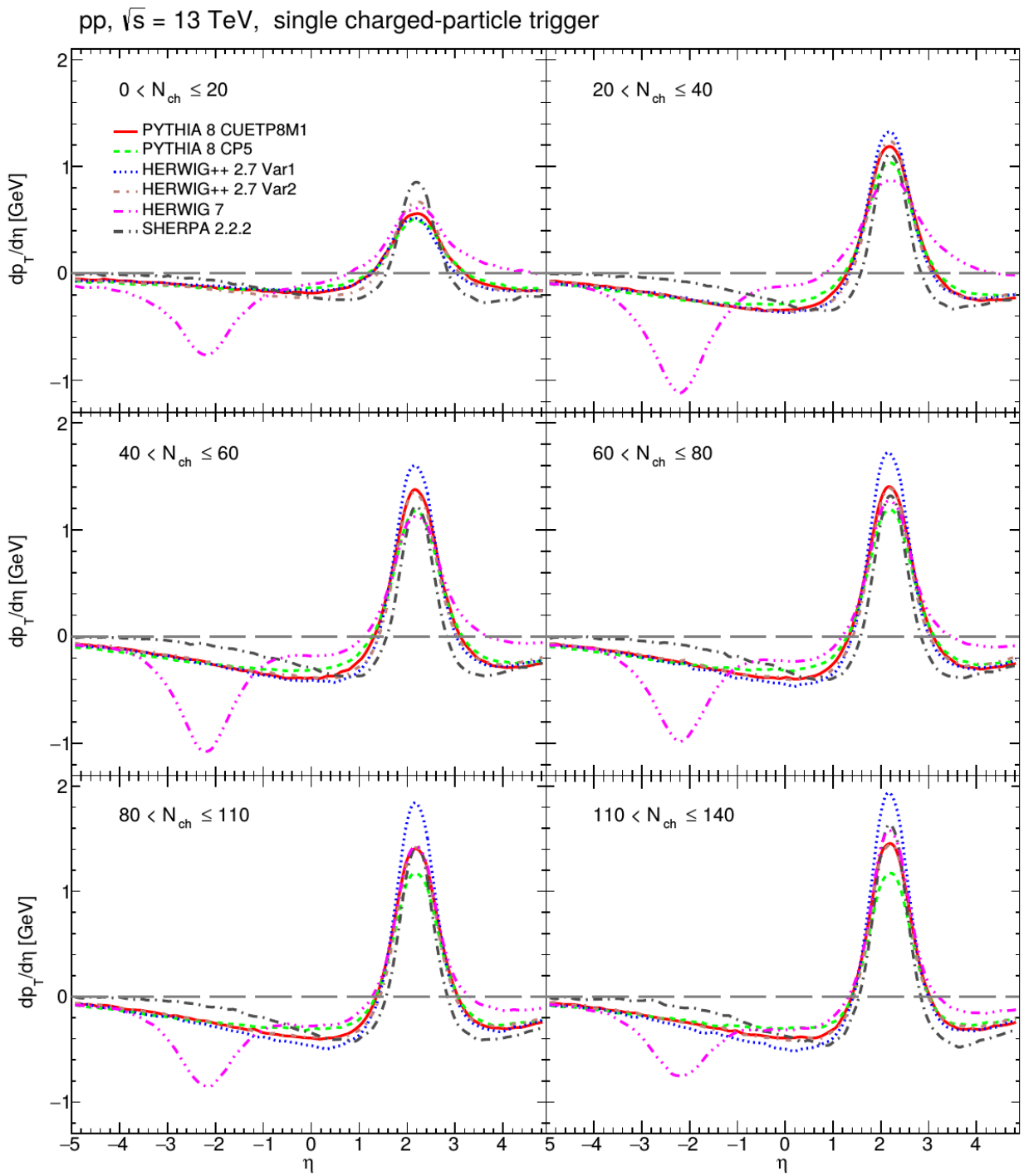
- Ptmin is the transition to soft MPI which is not showered, for Var1 more soft MPI (less particles in a jet smaller dale)

# 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.

# Updates - soft model

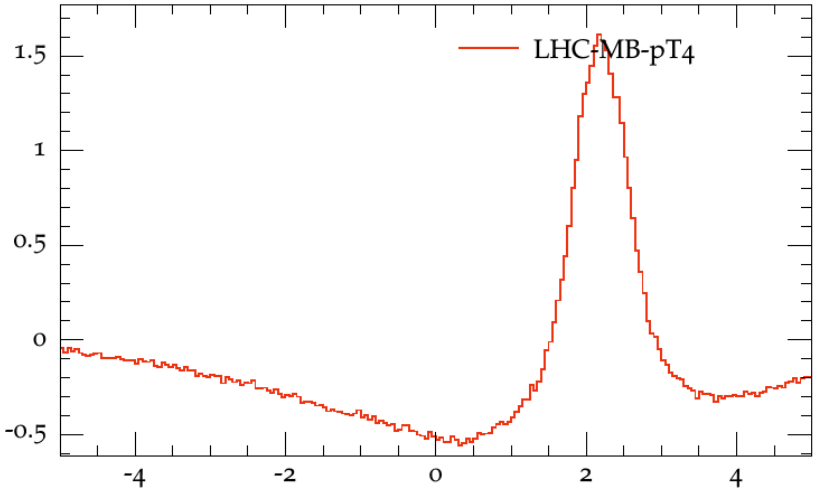
**Problems of soft model**

1. Remnant splitting procedure to generate soft ladder (now modified Jadach algorithm)
2. pT of soft particles correlated (see minijet correlation paper) (fixed with new kinematics)

**Slide from last week: talk by Patrick Kirchgaeßer**

The model was tuned to and described data sets.

It gives some additional discrimination power



# 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.

- It was already used to improve kinematics new soft model in Herwig

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

Thank you for your attention!

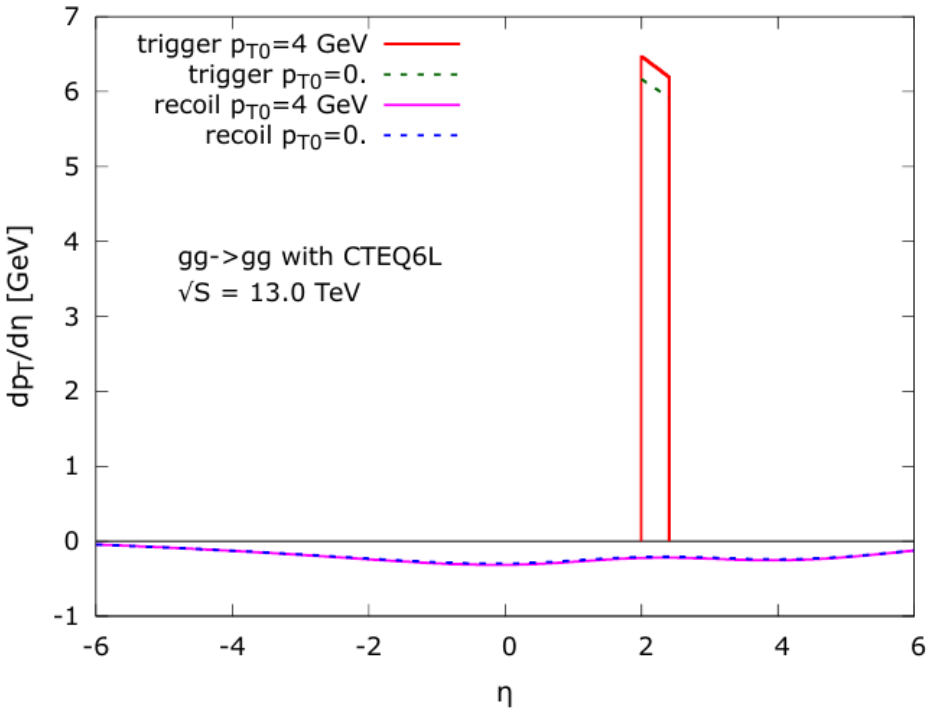
# Summary and outlook

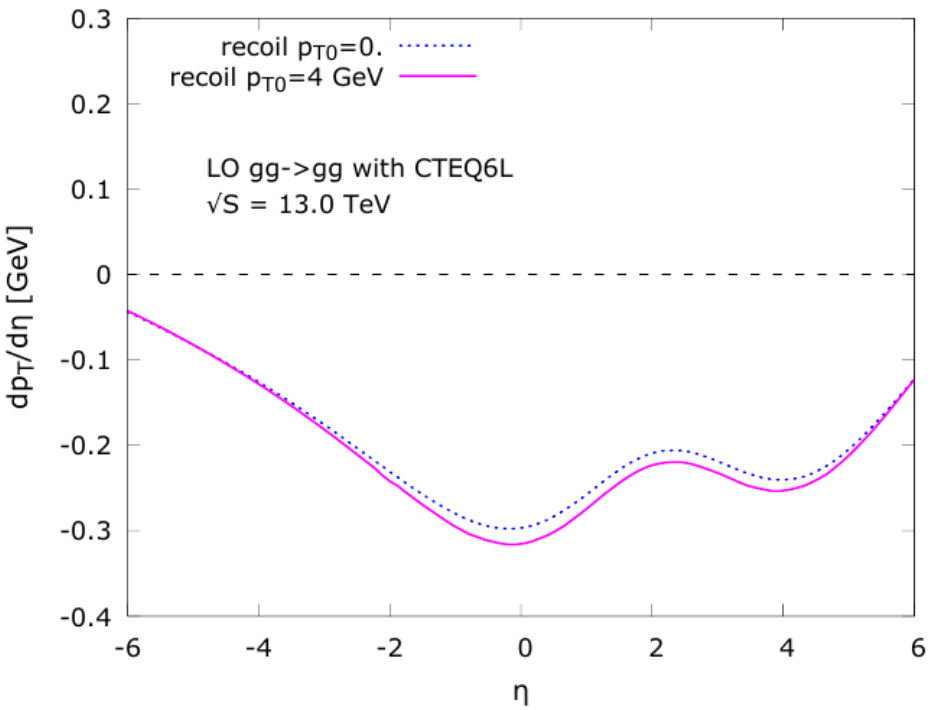
- We have introduced a new observable which probes interplay between the soft and hard physics at moderate pT via probing long and short range rapidity correlations of transverse momenta of charged particles/minijets.

- 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.

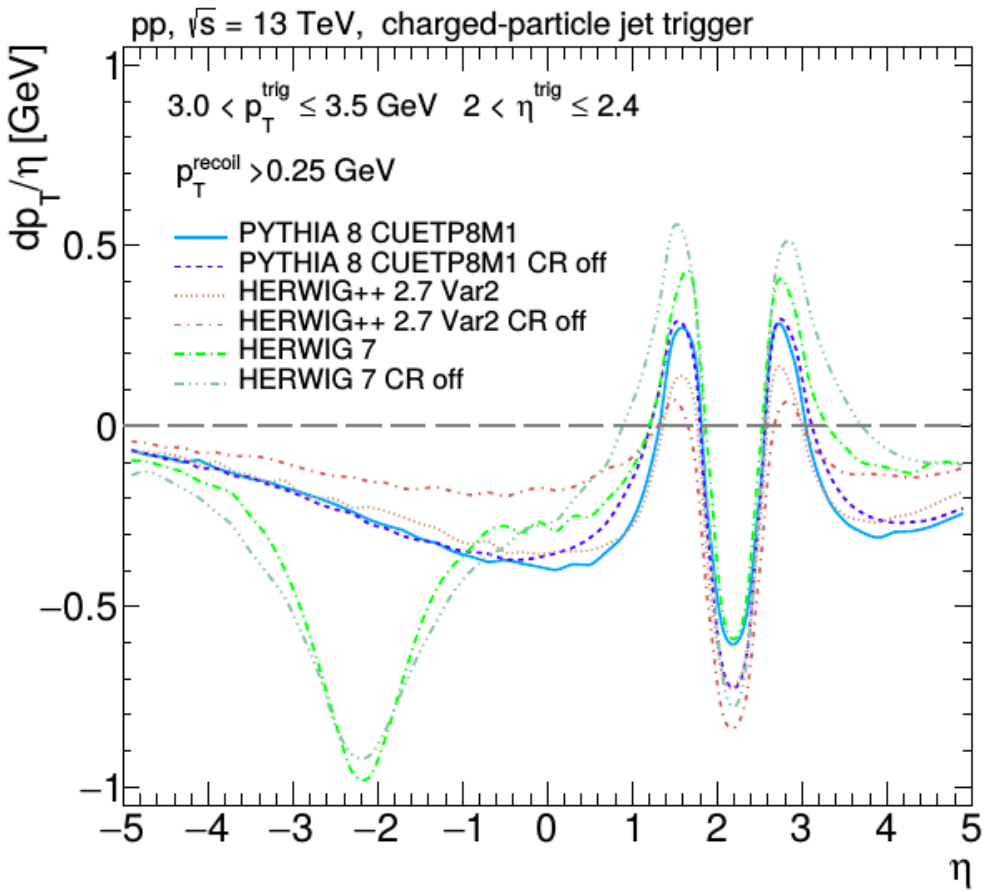
- Outlook:
  - measure it! :)
  - it would be also interesting to study such correlations in pA and AA
  - extended the method by using as trigger particles two hadrons with a given azimuthal angle difference.

# Hard matrix element LO



# Results colour reconnection effects




- Some sensitivity especially in Herwig