

Azimuthal correlations in dijet events at NLO with the PB method

03.05.2022

A. Bermúdez Martínez on behalf of the PB group

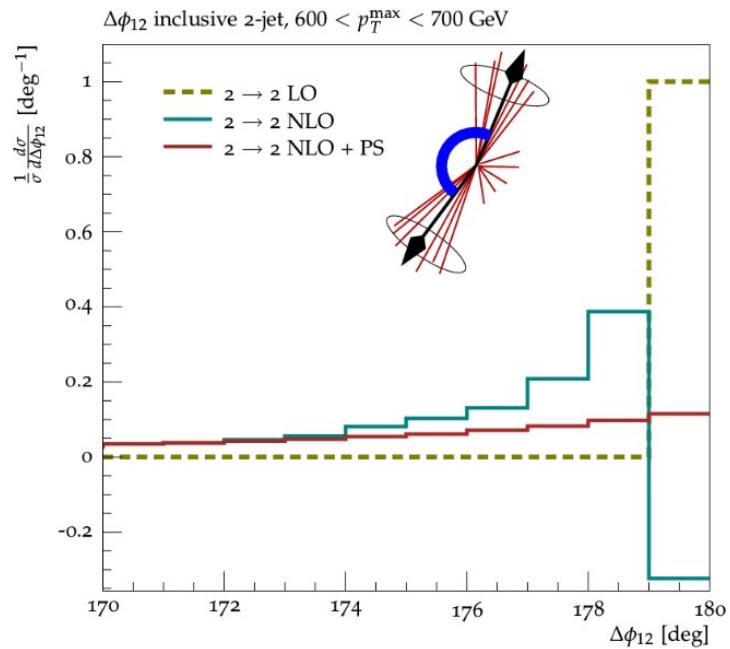
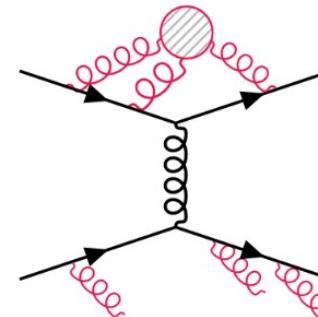
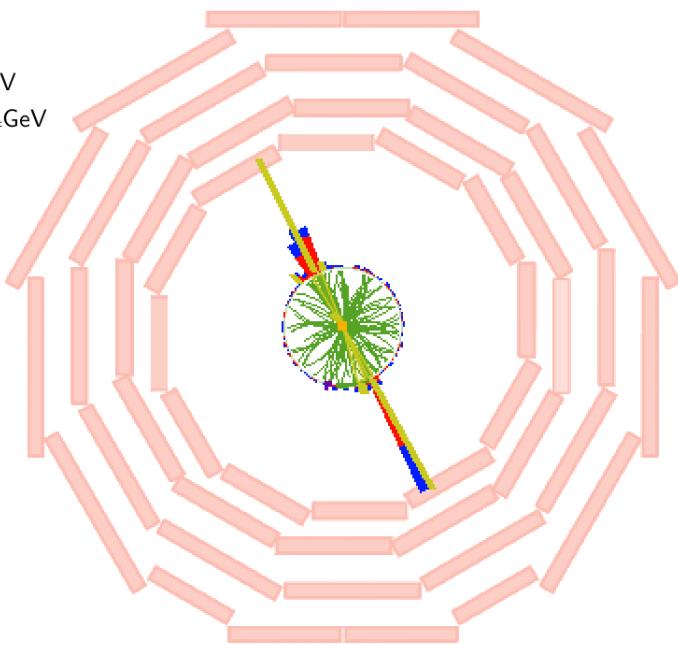
Eur.Phys.J.C 82 (2022) 1, 36



Azimuthal correlation in dijet events

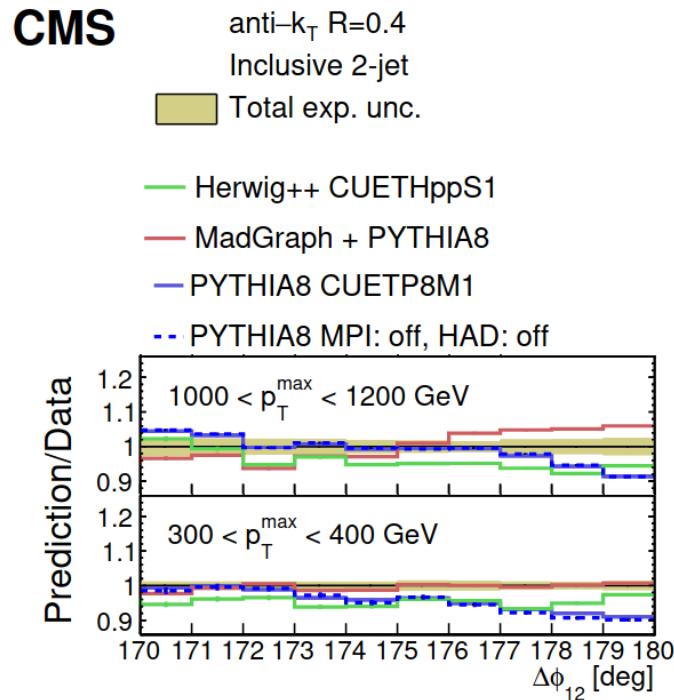
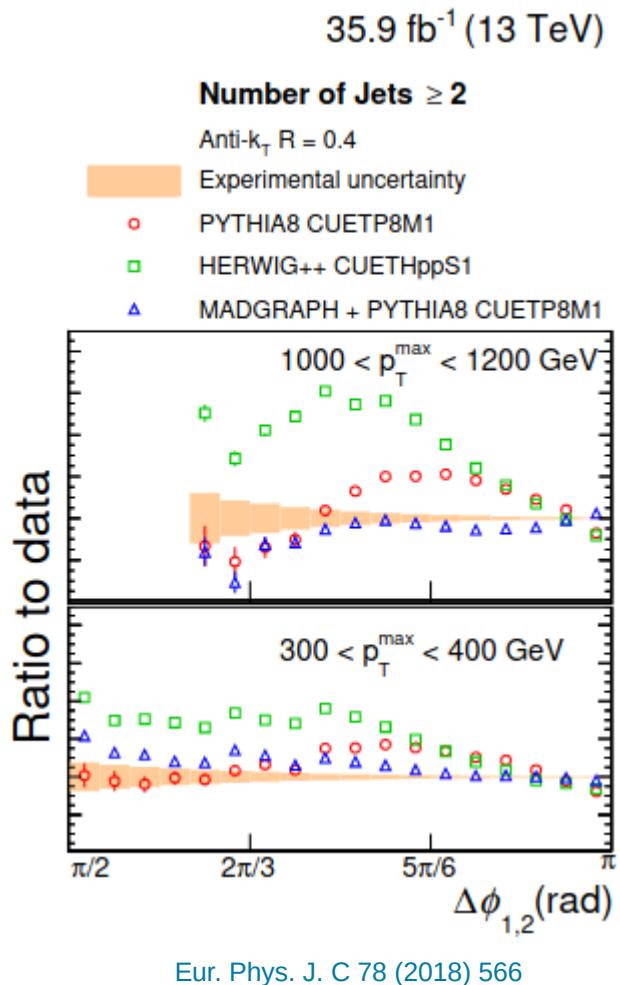
CMS Experiment at LHC, CERN
Data recorded: Sun Aug 14 13:01:17 2016 CEST
Run/Event: 278820 / 21368498
Lumi section: 18

Leading $p_T = 696\text{GeV}$
Subleading $p_T = 694\text{GeV}$
Leading $y = 0.23$
Subleading $y = 0.57$
 $\Delta\phi_{12} = 178.2^\circ$



- Test to QCD
- Sensitive to resummation
- Sensitive to hard radiation
- Possible factorization breaking effects

Azimuthal correlation in dijet events



- Deviations of up to 50% at low Δϕ
- Deviations of ~10% at high Δϕ

The PB method

Parton Branching (PB) method

- Evolution of TMDs (and collinear PDFs)
 - Resummation of soft gluons at LL and NLL
 - Solution valid at LO, NLO and NNLO
 - Determination of TMDs from the fully exclusive solution
 - **Backward evolution fully determines the TMD shower**
- consistently treats perturbative and non-perturbative transverse momentum effects

FH et al. [[PLB 772 \(2017\) 446–451](#)]
FH et al. [[JHEP 2018, 70 \(2018\)](#)]
ABM et al. [[PRD 99, 074008 \(2019\)](#)]

PB formulation of TMD evolution

[slide by M. van Kampen]

PB evolution equation for TMDs $\tilde{\mathcal{A}}_a(x, k_t^2, \mu^2)$ can be solved iteratively with the Monte Carlo method:

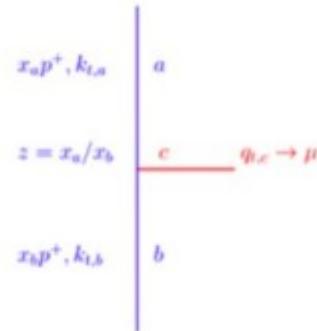
$$\begin{aligned} \tilde{\mathcal{A}}_a(x, k_t^2, \mu^2) = & \Delta_a(\mu^2, \mu_0^2) \tilde{\mathcal{A}}_a(x, k_{t,0}^2, \mu_0^2) + \\ & + \sum_b \left[\int \frac{d^2\mu'}{\pi\mu'^2} \int_x^{z_M(\mu')} dz \Theta(\mu^2 - \mu'^2) \Theta(\mu'^2 - \mu_0^2) \right. \\ & \times \left. \frac{\Delta_a(\mu^2, \mu_0^2)}{\Delta_a(\mu'^2, \mu_0^2)} P_{ab}^{(R)}(\alpha_s(q_t), z) \tilde{\mathcal{A}}_b\left(\frac{x}{z}, \underbrace{k_{t,b} - q_{t,c}}_{k_{t,a}}, \mu'^2\right) \right] \end{aligned}$$

$P_{ab}^{(R)}(\alpha_s, z)$ real splitting function (resolvable branching probability),
 $\Delta_a(\mu^2, \mu_0^2)$ Sudakov (no branching probability)

$$P_{ab}^{(R)}(\alpha_s, z) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi} \right)^n P_{ab}^{(R)n-1}(z)$$

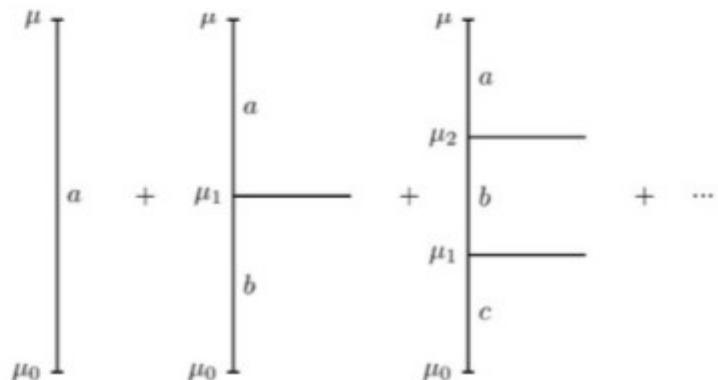
$$\Delta_a(\mu^2, \mu_0^2) = \exp \left(- \sum_b \int \frac{d\mu^2}{\mu^2} \int_0^{z_M} dz z P_{ab}^{(R)}(z, \alpha_s) \right)$$

JHEP 01 (2018) 070 [arXiv:1708.03279]



Kinematics in each branching governed by momentum conservation: $k_{t,b} = k_{t,a} + q_{t,c}$

Angular ordering condition: $q_t^2 = (1-z)^2 \mu'^2$



PB formulation of TMD evolution

[slide by M. van Kampen]

Backward evolution with PB method

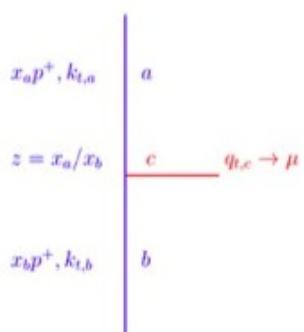
The TMD evolution equation can be used to do a backward evolution:

$$\frac{\partial}{\partial \ln \mu^2} \left(\frac{\tilde{A}_a(x, k_t, \mu)}{\Delta_a(\mu)} \right) = \sum_b \int_x^{z_M} dz P_{ab}^{(R)} \frac{\tilde{A}_b(x/z, k'_t, \mu)}{\Delta_a(\mu)},$$

normalize to $\frac{\tilde{A}_a(x, k_t, \mu)}{\Delta_a(\mu)}$ and integrate over μ' from μ_i down to μ_{i-1}

$$\Delta_{bw}(x, k_t, \mu_i, \mu_{i-1}) = \exp \left\{ - \sum_b \int_{\mu_{i-1}^2}^{\mu_i^2} \frac{d\mu'^2}{\mu'^2} \int_x^{z_M} dz P_{ab}^{(R)} \frac{\tilde{A}_b(x/z, k'_t, \mu')}{\tilde{A}_a(x, k_t, \mu')} \right\}.$$

This Sudakov is used as the no-branching probability in the TMD parton shower.

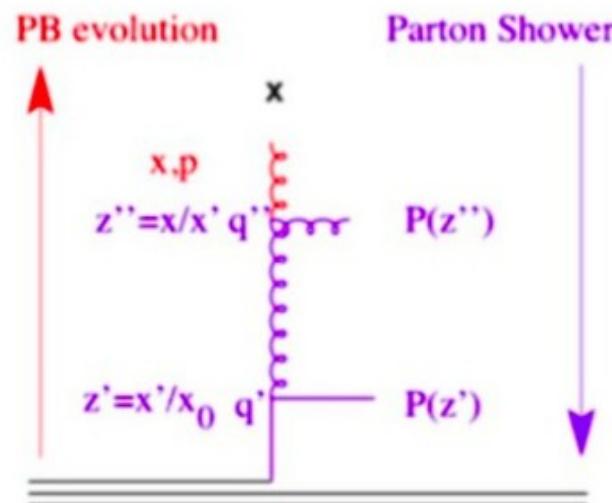


- In each splitting

$$\begin{aligned} \mathbf{k}_{t,b} &= \mathbf{k}_{t,a} + \mathbf{q}_{t,c} \\ &= \mathbf{k}_{t,a} + (1-z)\mu \end{aligned}$$

- Total transverse momentum:

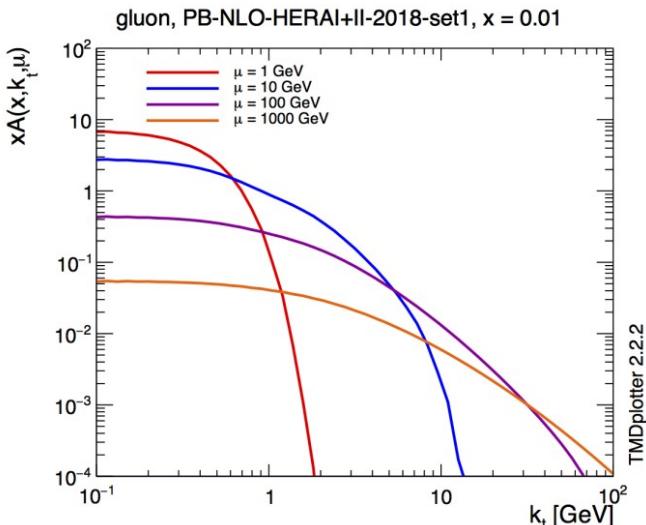
$$\mathbf{k}_t = \mathbf{k}_{t,0} + \sum_c \mathbf{q}_{t,c}$$



Implemented in the CASCADE event generator

S. Baranov et al. [Eur. Phys. J. C 81 (2021) 425]

Pert. and non-pert. PB TMD contributions



- ISR broadens initial distribution

ABM et al. [PRD 99, 074008 (2019)]

- DIS measurements from HERA I+II
- fitting procedure in a nutshell:
 - parametrize the integrated distribution at Q_0
 - with the PB method evolve the TMD to $Q > Q_0$
(implemented in xFitter)
 - fit the measurements and extract the initial parametrization
 - store the TMD in a grid for later use
(TMDlib, complementary slides)

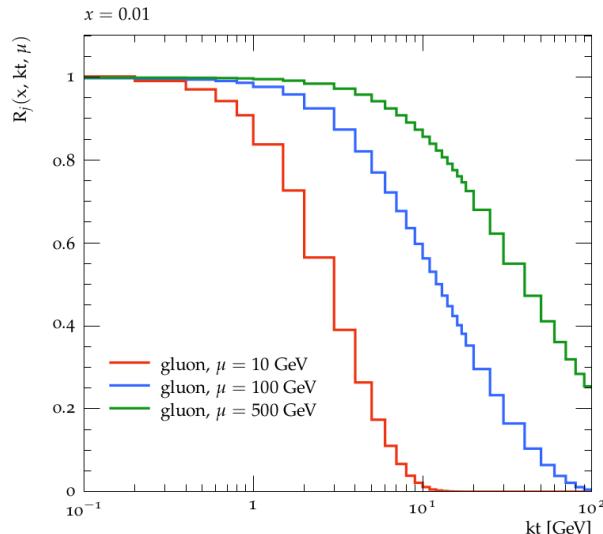
N. A. Abdulov et al. [Eur. Phys. J. C 81 (2021) 752]

Consider the integrated distribution above the jet pT scale:

$$a_j(x, \mathbf{k}, \mu^2) = \int \frac{d^2 \mathbf{k}'}{\pi} \mathcal{A}_j(x, \mathbf{k}', \mu^2) \Theta(\mathbf{k}'^2 - \mathbf{k}^2)$$

- e.g. probability of 0.3 that the gluon develops a kt larger than 20 GeV, for $\mu = 100$ GeV

- TMD evolution effects crucial at describing jet production



ABM et al. [arXiv:2107.01224]

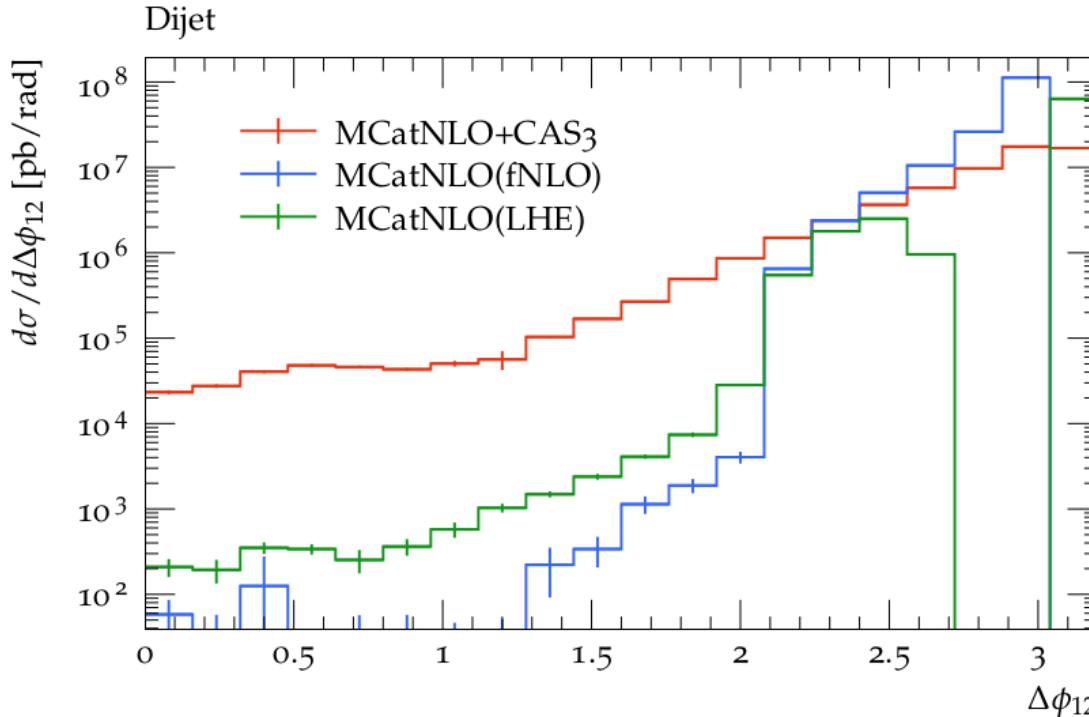
Application to dijet azimuthal correlations

Application to dijet azimuthal correlations

Matching PB evolution to NLO calculations

- Combined with MC@NLO, also for the case of DY
- Using HERWIG6 subtraction terms
- PB-TMD parton shower unfolds the TMD distribution
- Parton shower implemented in the CASCADE generator

ABM et al. [PRD 100, 074027 (2019)]
ABM et al. [EPJC 80, 598 (2020)]

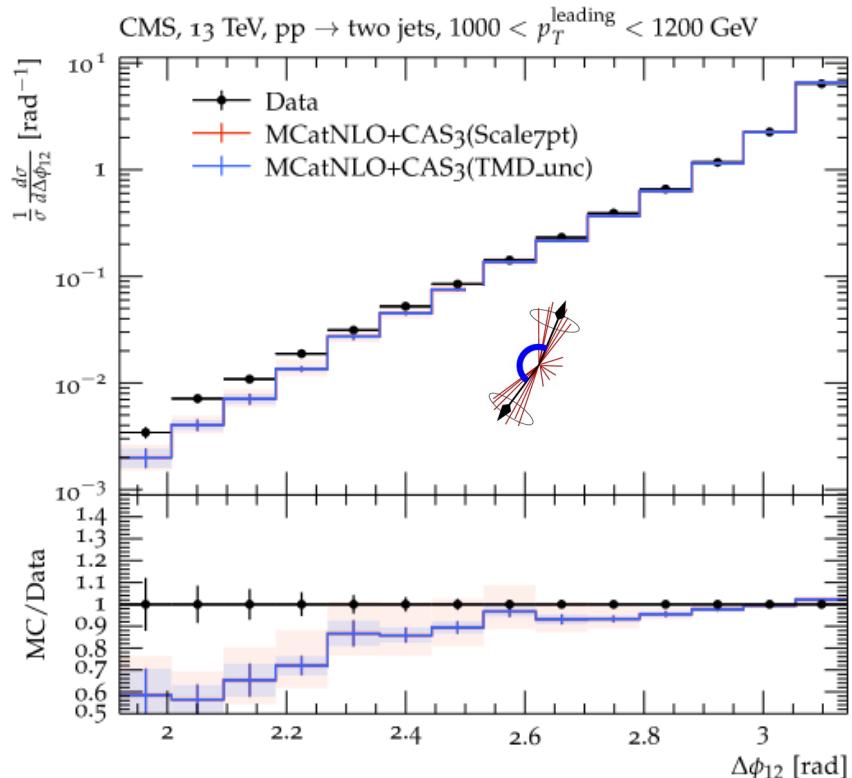
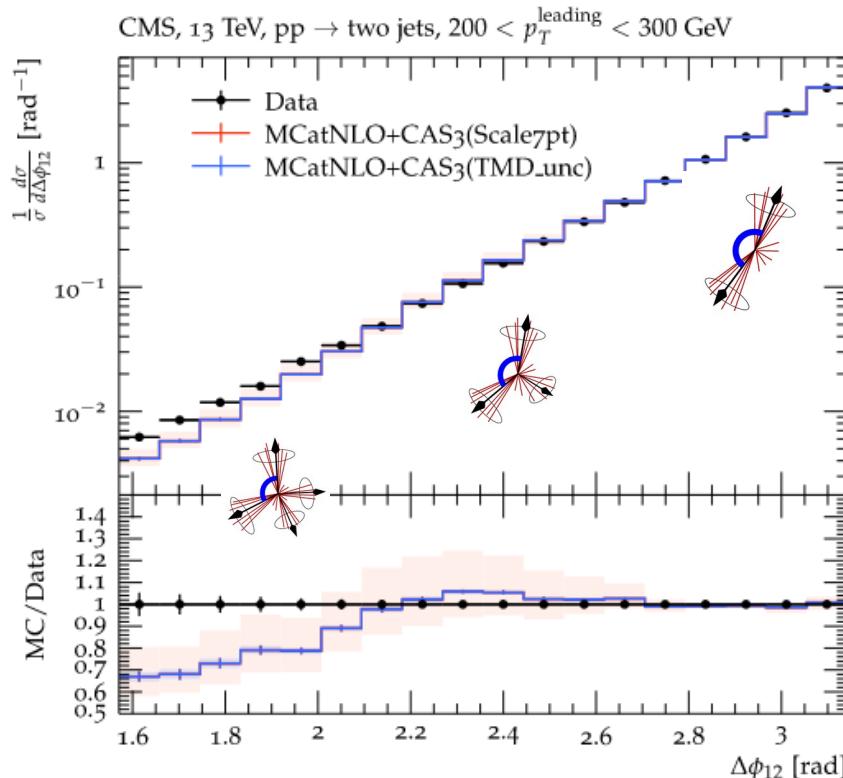


Application to dijet azimuthal correlations

Results in the wider $\Delta\phi$

- Good description at high and intermediate $\Delta\phi$
- Missing higher orders at low $\Delta\phi$
- Scale variations are main source of uncertainty

Eur. Phys. J. C 78 (2018) 566

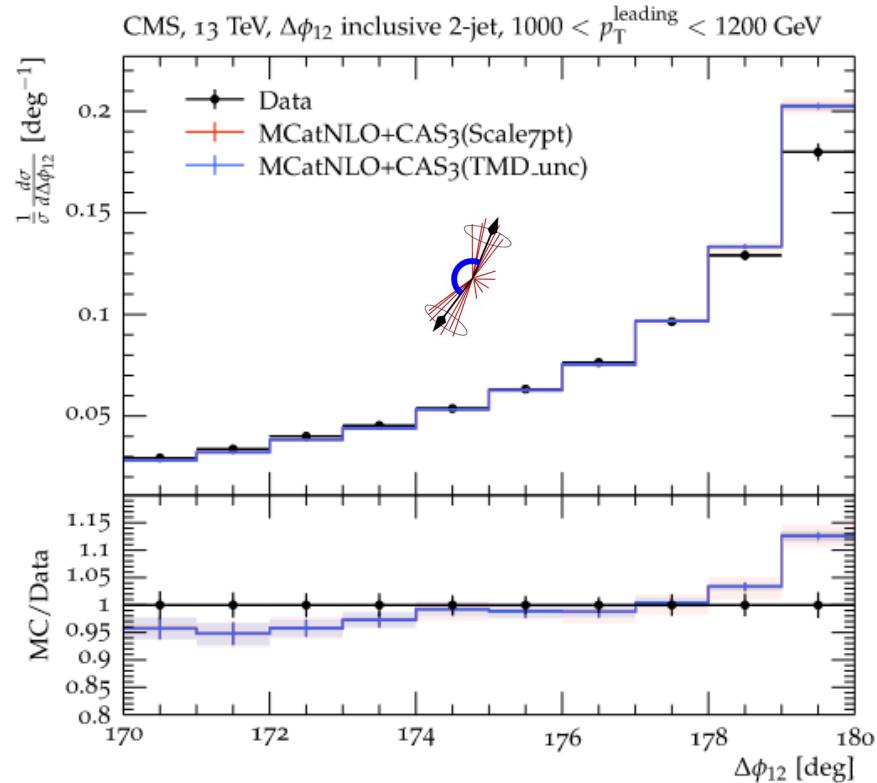
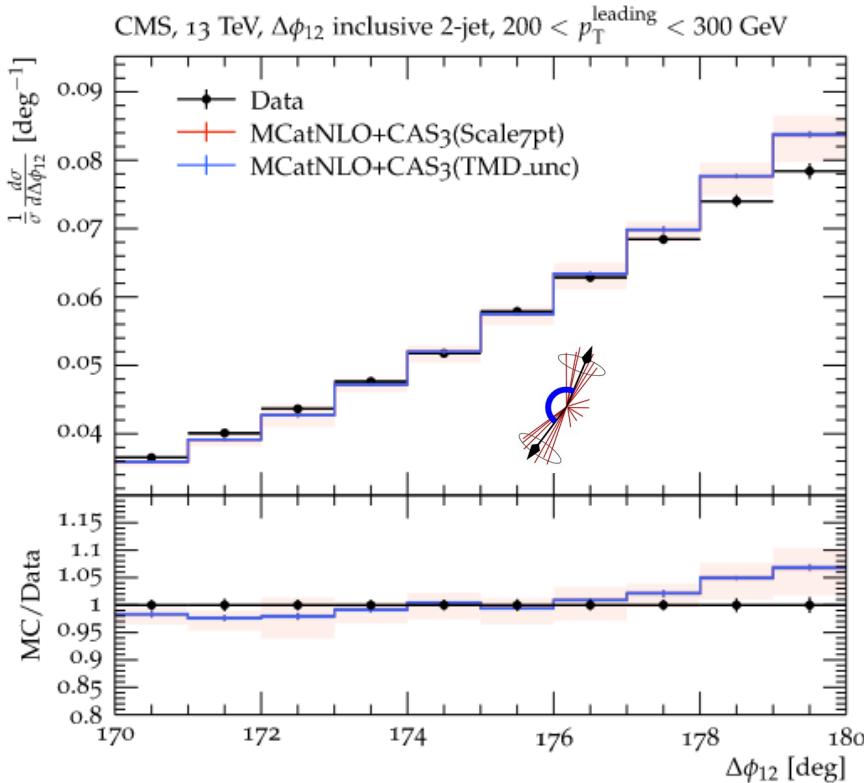


Application to dijet azimuthal correlations

Results in the back-to-back region

- Resummation of soft radiation in the TMD evolution crucial
- Discrepancy only significant at very high pT and very large $\Delta\phi$

Eur. Phys. J. C 79 (2019) 773

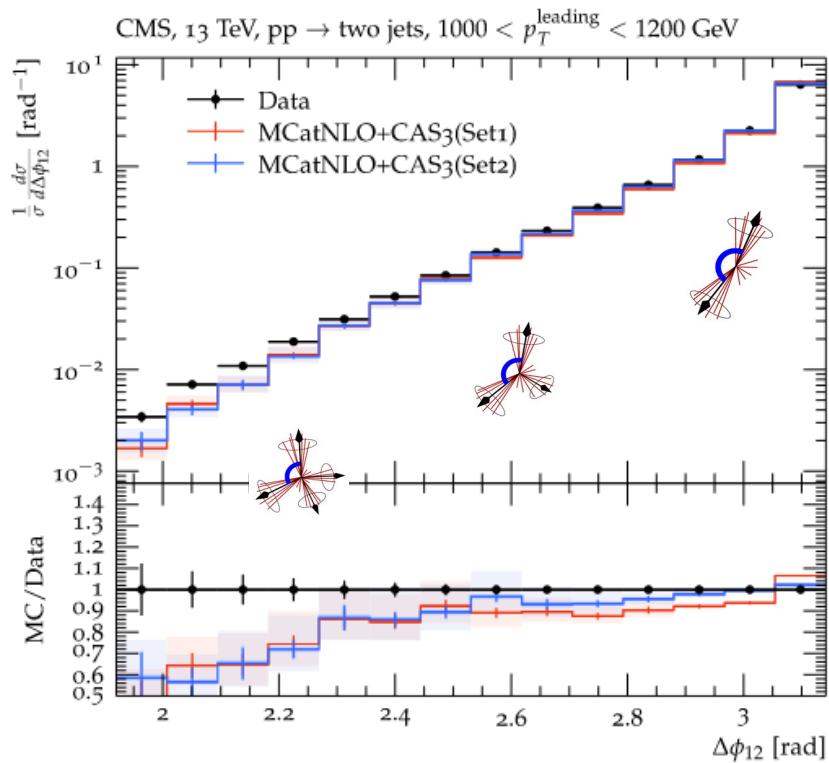


Application to dijet azimuthal correlations

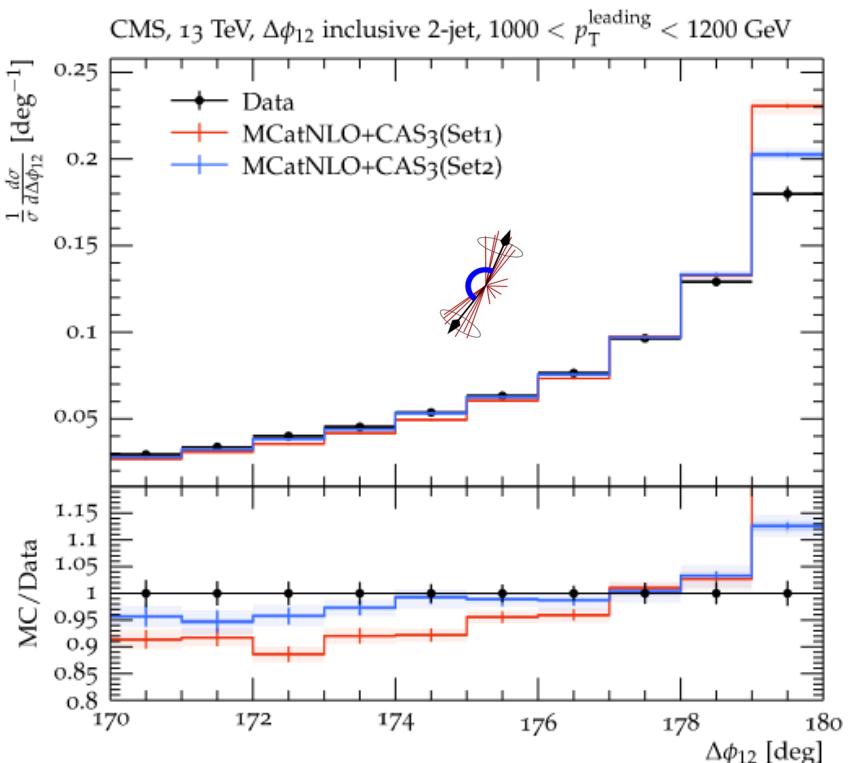
Strong coupling argument

- pT as argument (set2) has a critical effect at better describing the large $\Delta\phi$ region

Eur. Phys. J. C 78 (2018) 566



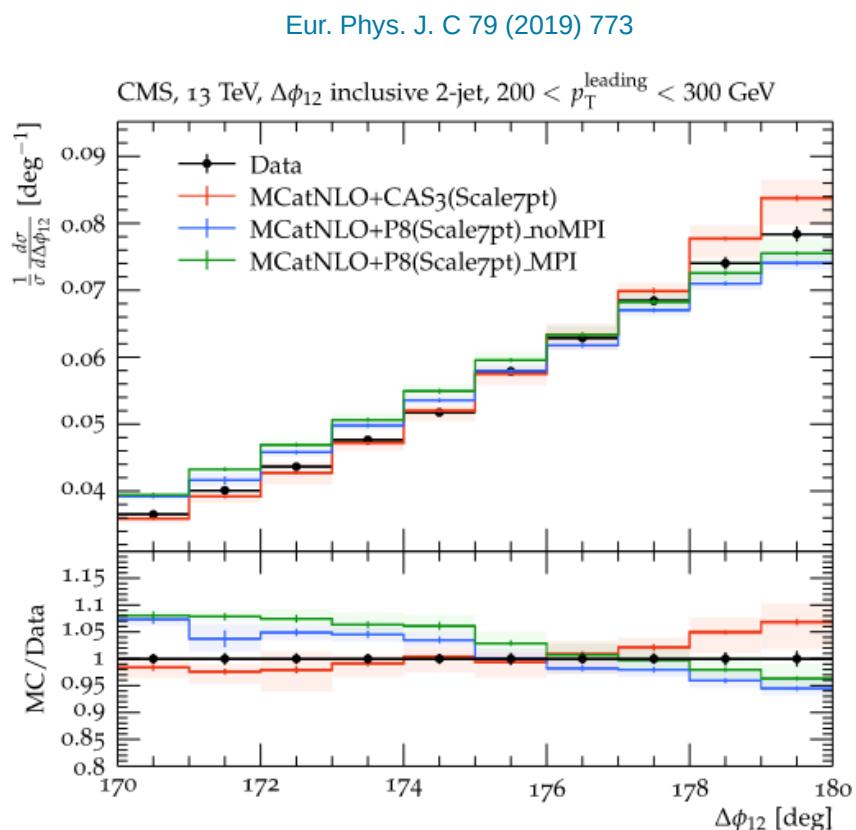
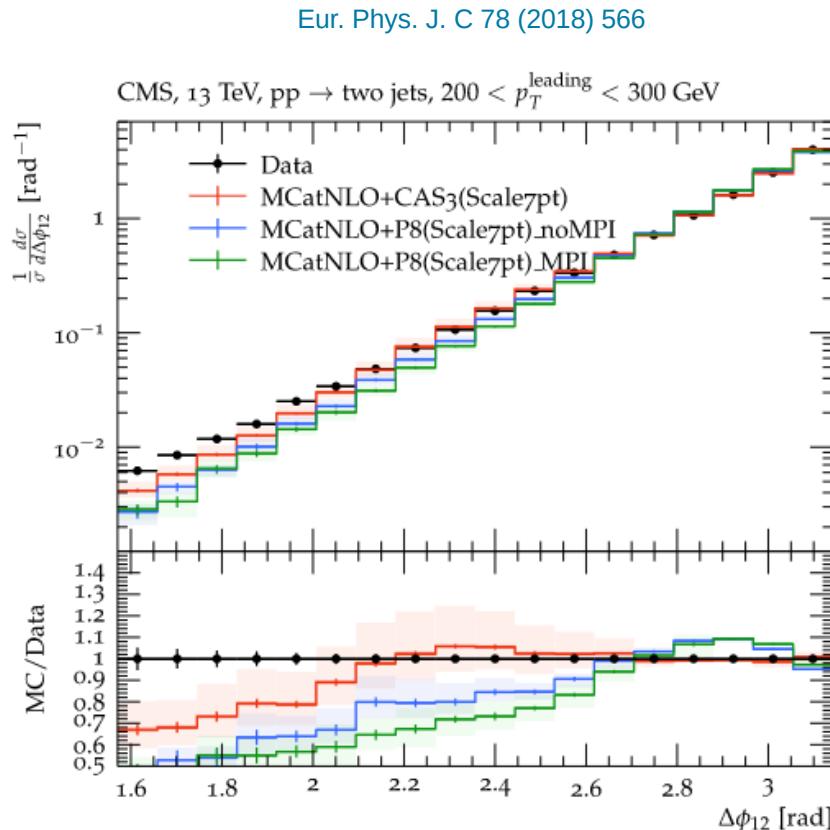
Eur. Phys. J. C 79 (2019) 773



Application to dijet azimuthal correlations

MPI effects

- MPI effects are small in the studied phase space
- Sizable differences in shape between PB-TMD and MC@NLO+P8



Conclusions

- PB-TMD parton shower match to NLO calculations provides a good description of intermediate and high $\Delta\phi$ regions
- At low $\Delta\phi$, missing higher order contributions are significant
- Deviations observed at very large $\Delta\phi$, where factorization breaking effects could contribute
- First TMD prediction for jet production at the LHC

Thank you