TMD Evolution and Multi-Jet Merging

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Resummation, Evolution, Factorization 2020

Why TMDs?

R. A. Martinez et al. [APP B46 (2015) 12, 2501–2534]

TMD: Transverse momentum dependent parton distribution

- Small transverse momentum phenomena
- Small-x phenomena
- DY, and semi-inclusive DIS
- Transverse momentum effects from intrinsic kt and evolution

Parton Branching (PB) method

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

- 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**

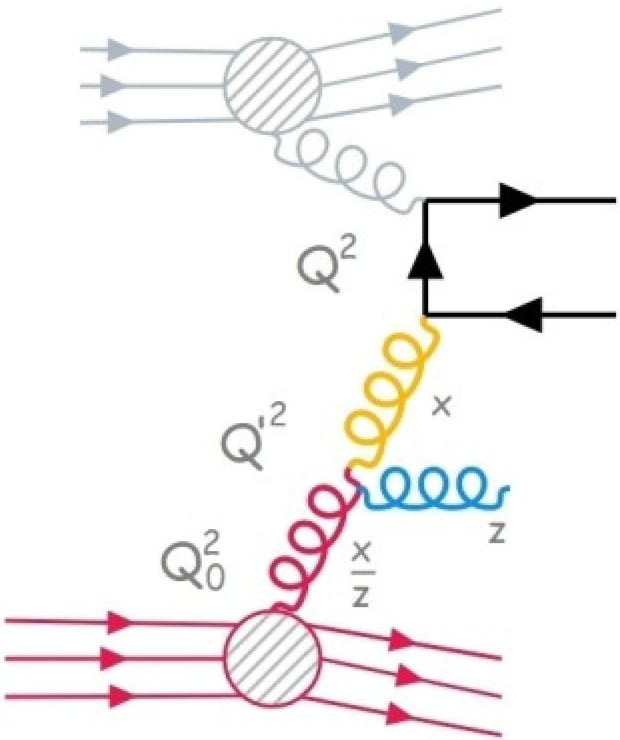
→ consistently treats perturbative and non-perturbative transverse momentum effects

PB method

PB iterative solution:

$$A_a^{(1)}(x, \mathbf{k_t}; Q^2) = \Delta_a(Q^2, Q_0^2) A_a(x, \mathbf{k_t}; Q_0^2) +$$

$$+ \sum_b \int_{Q_0^2}^{Q^2} \frac{d^2\mathbf{Q}'}{\pi Q'^2} \frac{\Delta_a(Q^2, Q_0^2)}{\Delta_a(Q'^2, Q_0^2)} \int_x^{z_M} dz P_{ab}^{(R)}\left(z, \alpha_s(Q'^2)\right) \Delta_b(Q'^2, Q_0^2) A_b\left(\frac{x}{z}, \mathbf{k_t} + (1-z)\mathbf{Q}'; Q_0^2\right)$$



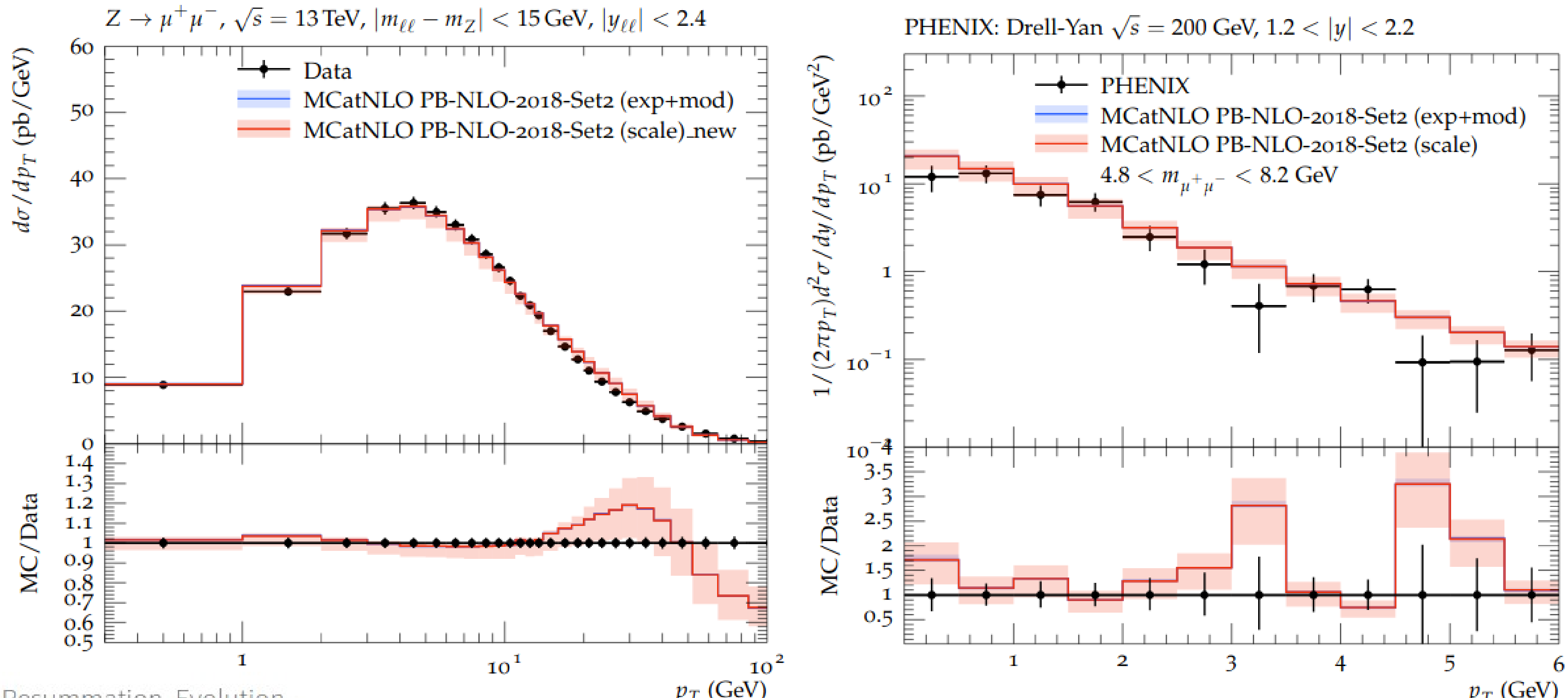
- kinematics of the splittings is known
- physics ➡ mapping of evolution variables to splitting kinematics
- TMD from cumulative kt of the branchings in forward PB evolution
- **Initial-state shower fully determined by TMD and its backward PB evolution**

PB method

Achievements

- TMD determination and evolution
- Valid for on- and off-shell ME calculations
- Combined with MC@NLO
- **Excellent description of low pT DY spectrum**
- **First simultaneous description of both low and high-mass DY pT spectrum**

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

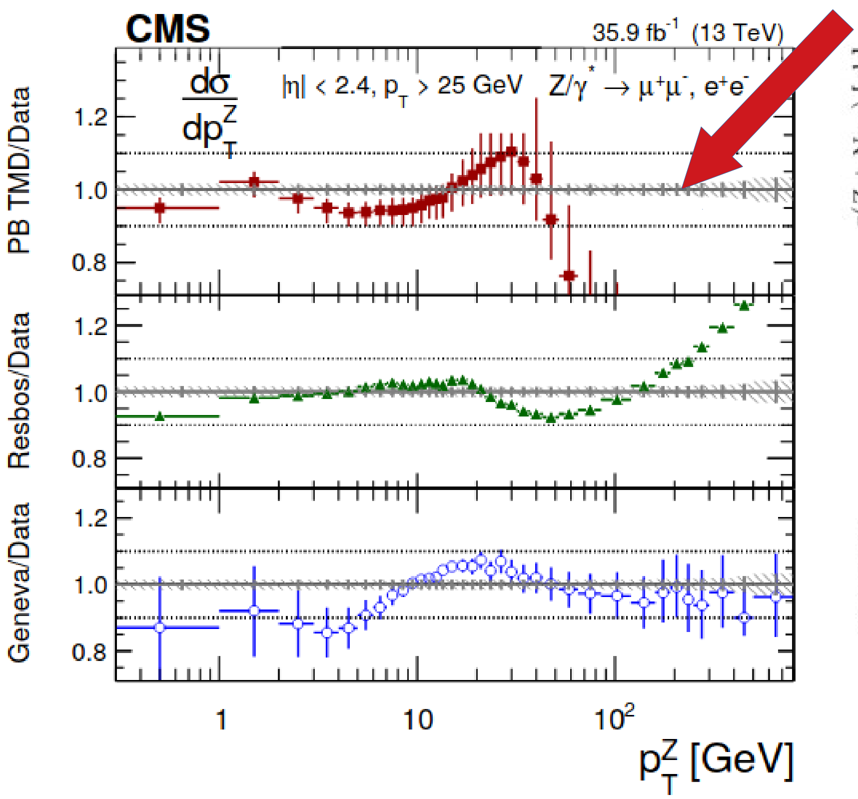


PB method

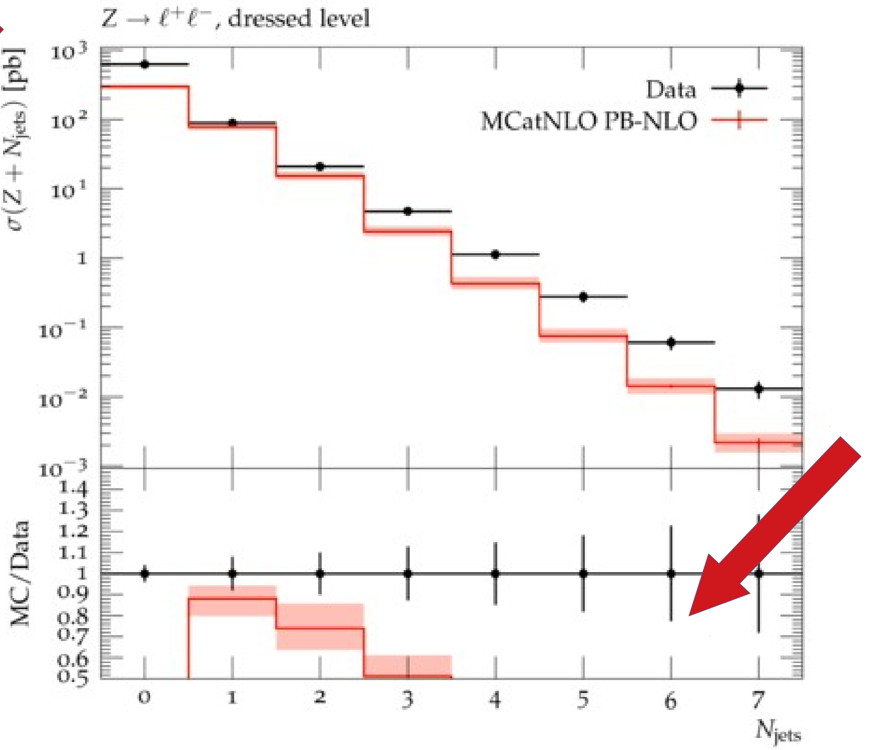
However

- Both high pT recoil and corresponding number of jets not well described
- **Need for higher order corrections**

CMS Collaboration [JHEP 2019, 61 (2019)]



ATLAS data: [Eur. Phys. J. C77 (2017) 361]



What we want:

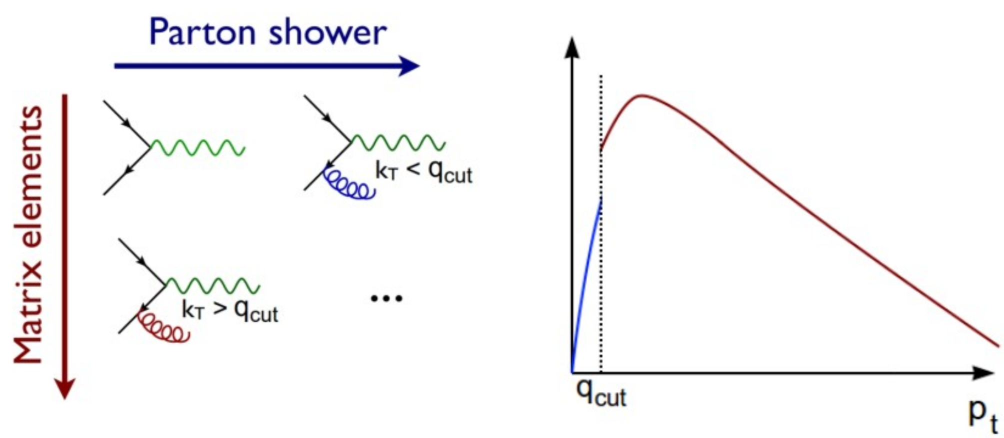
- Treat perturbative and non-perturbative TMD effects
- Include soft gluon resummation
- Include corrections from higher-order fixed-order calculations

Develop a method to combine PB-TMDs with multi-jet calculations

Multi-jet merging

- Make higher-order ME exclusive by Sudakov suppression
- Avoid double counting between PS and ME

- Improvement of hard, wide-angle emissions
- Description of high-pT phenomena

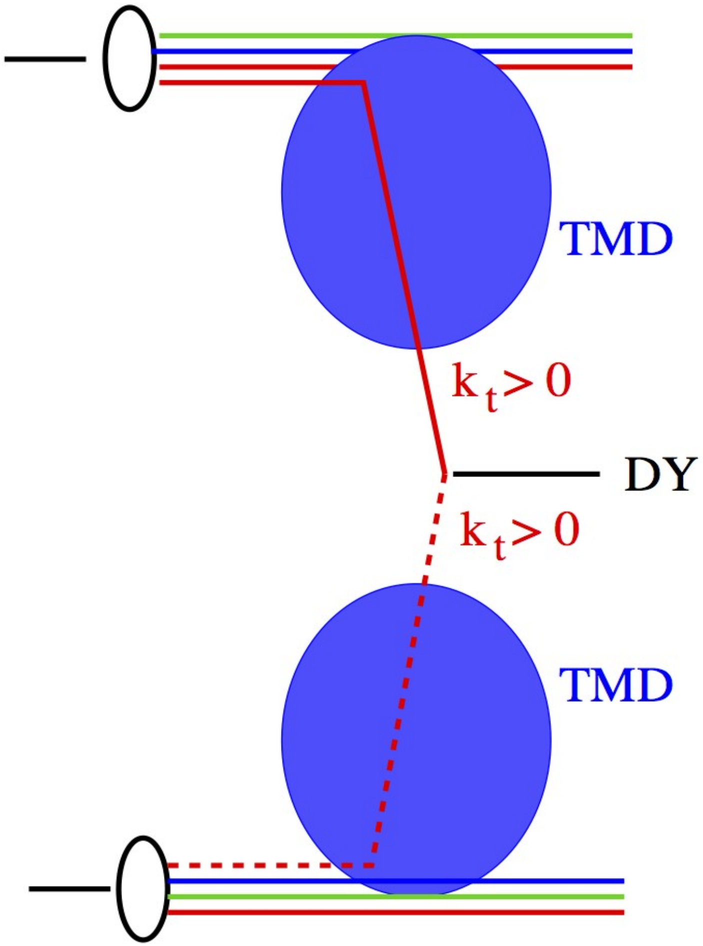


- 1st emission PS: $\mathcal{R}^{PS}(p_t^2) \times \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$
- 1st emission ME: $\mathcal{R}(p_t^2) \longrightarrow \mathcal{R}(p_t^2) \times \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$

MLM-TMD method

ABM et al. [paper in preparation]

- Evaluate the ME for n-jet cross sections
- Reweight the strong coupling according to shower history
- **Evolve the ME using the TMD PB evolution**
- **Shower the events using the backward PB evolution for ISR**
- **Apply the MLM(*) prescription between the PB-evolved ME and the showered events**



New merging procedure applicable to TMDs!

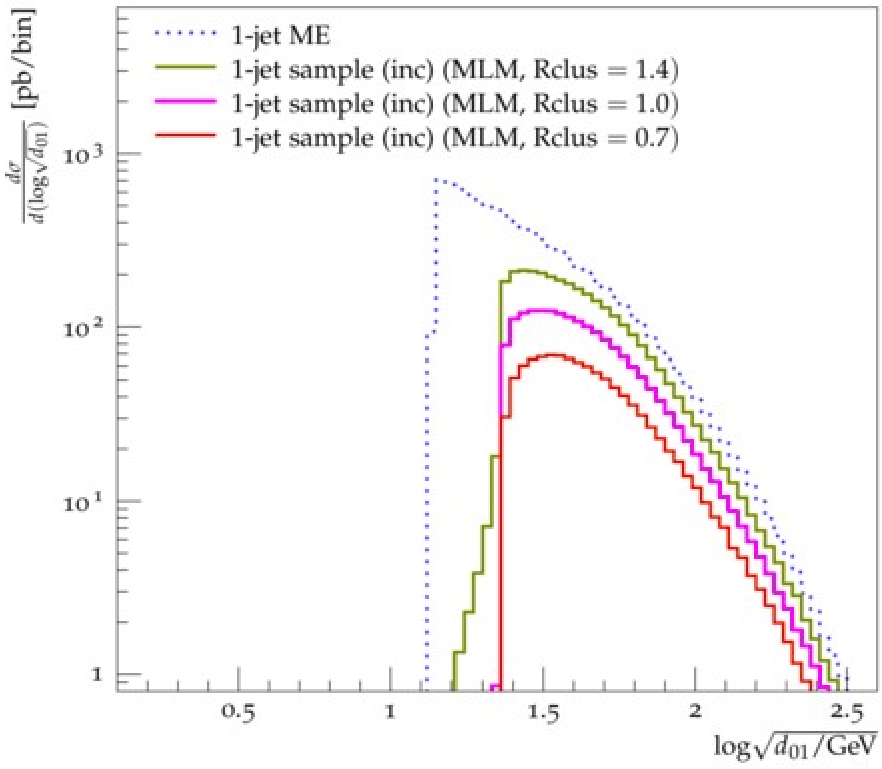
(*) M. L. Mangano [NPB 632 (2002) 343–362]

From MLM to MLM-TMD

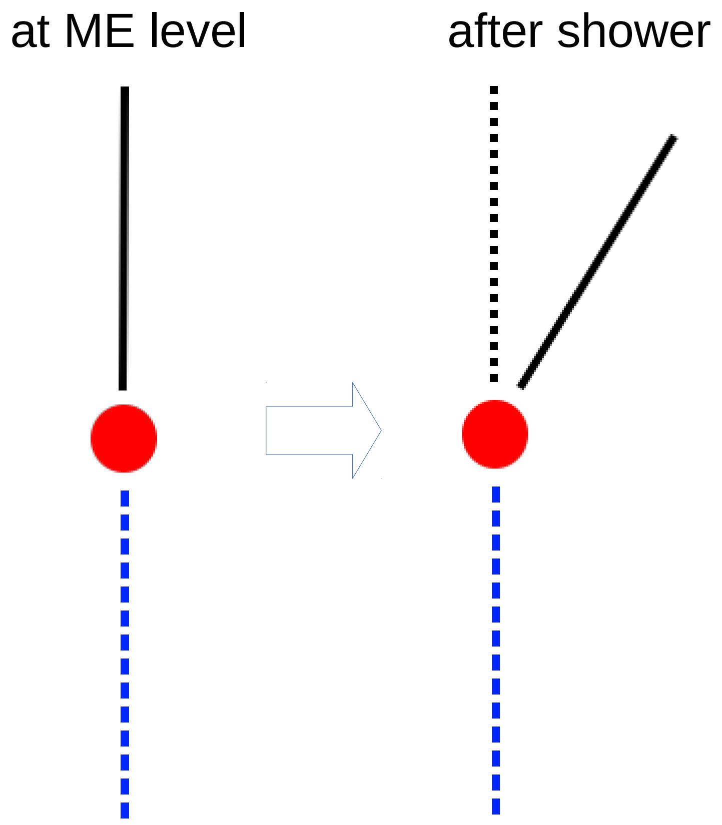
ABM et al. [paper in preparation]

What about the original MLM?

- very strong dependence on Rclus
- at large scales ME accuracy lost!



d(n,n+1): square of scale at which (n+1)-jet configuration becomes n-jet



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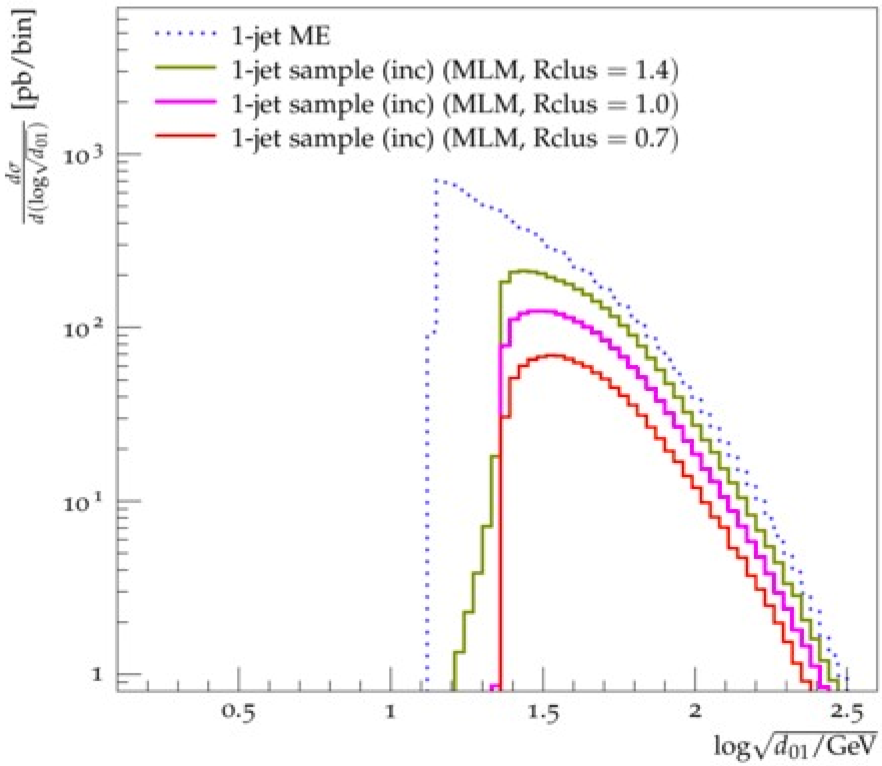

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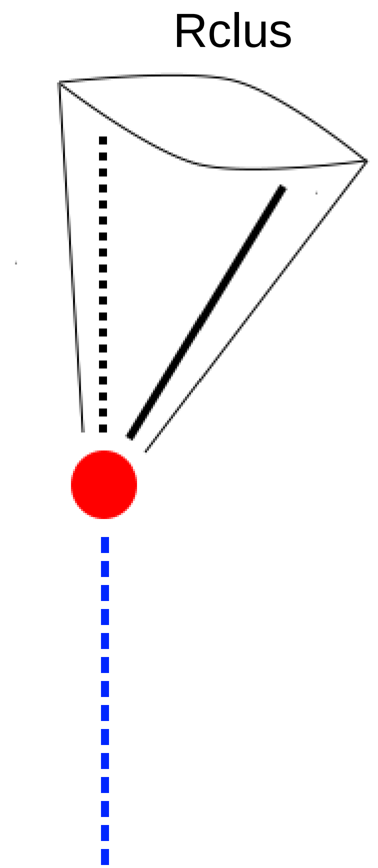

reject non-matched events

From MLM to MLM-TMD

ABM et al. [paper in preparation]

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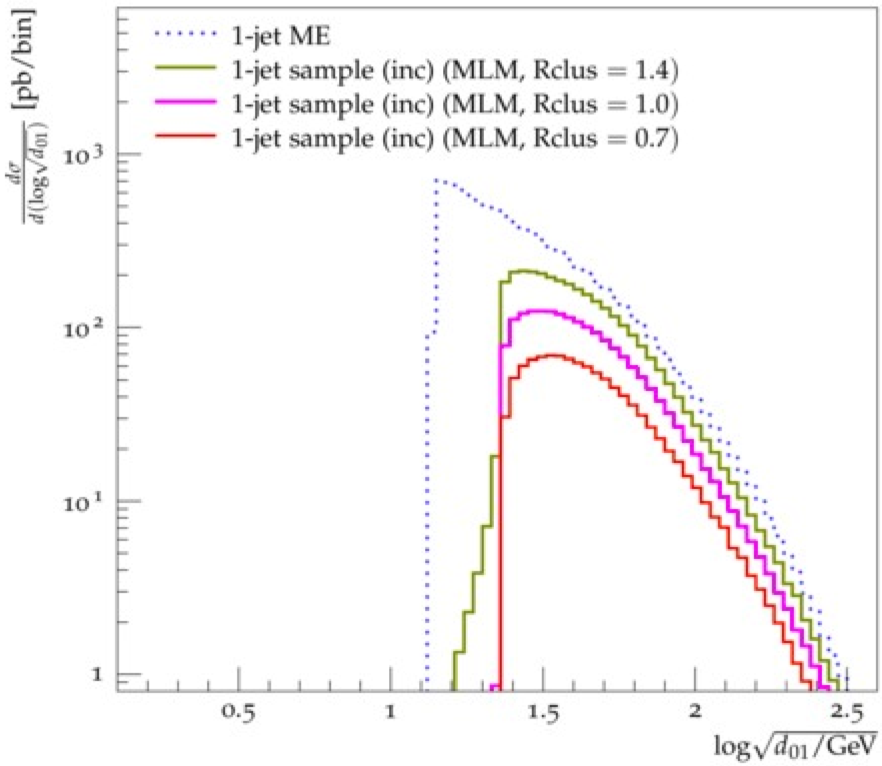

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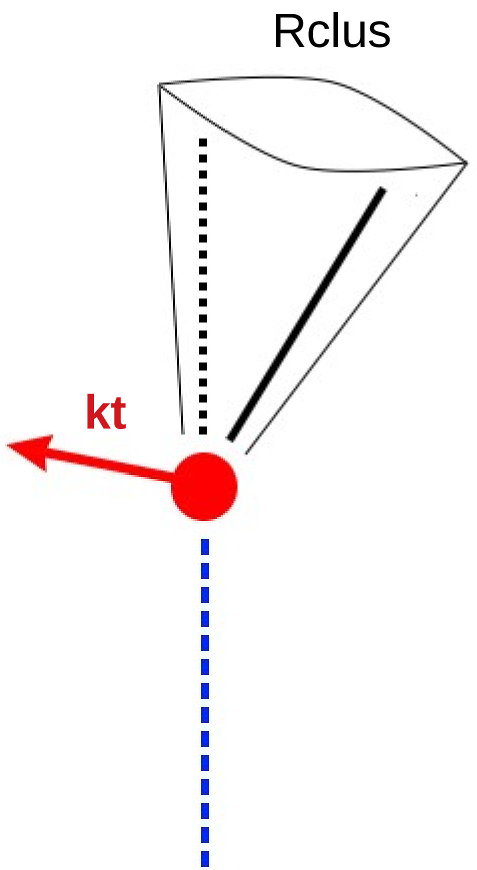


ktmax = **kt**max(Rclus) !

Rclus translates into a maximum TMD evolution scale

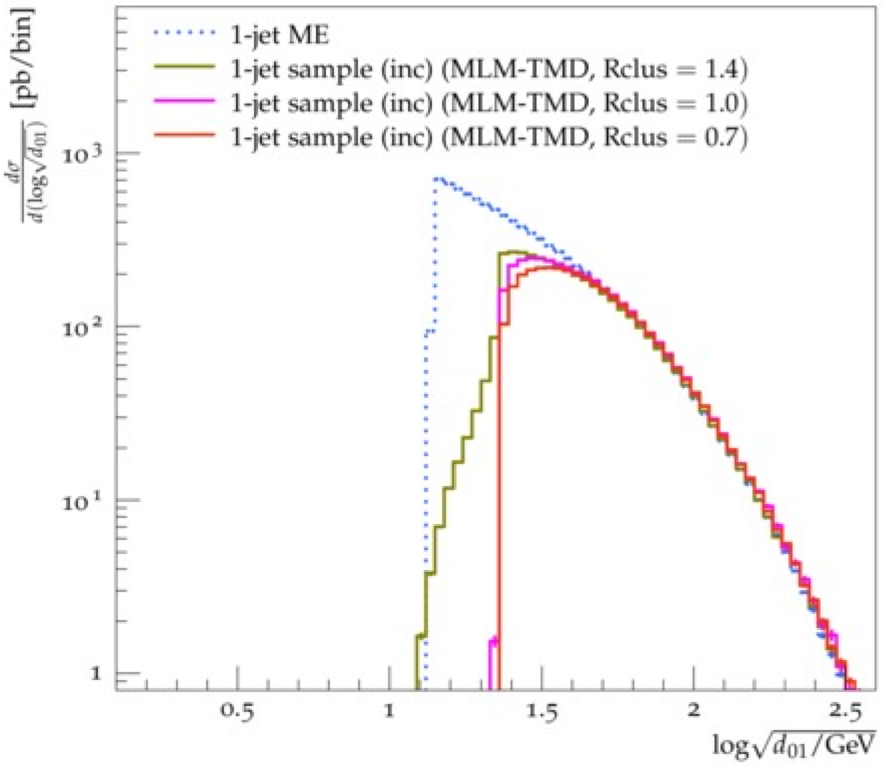
⇨ original MLM incompatible with PB TMD evolution

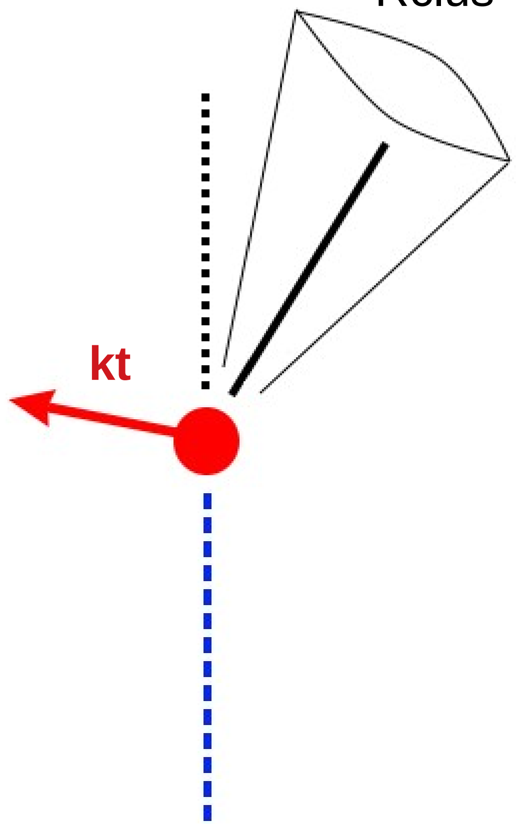
From MLM to MLM-TMD

ABM et al. [paper in preparation]

MLM-TMD

- little dependence on Rclus
- at large scales ME accuracy recovered!



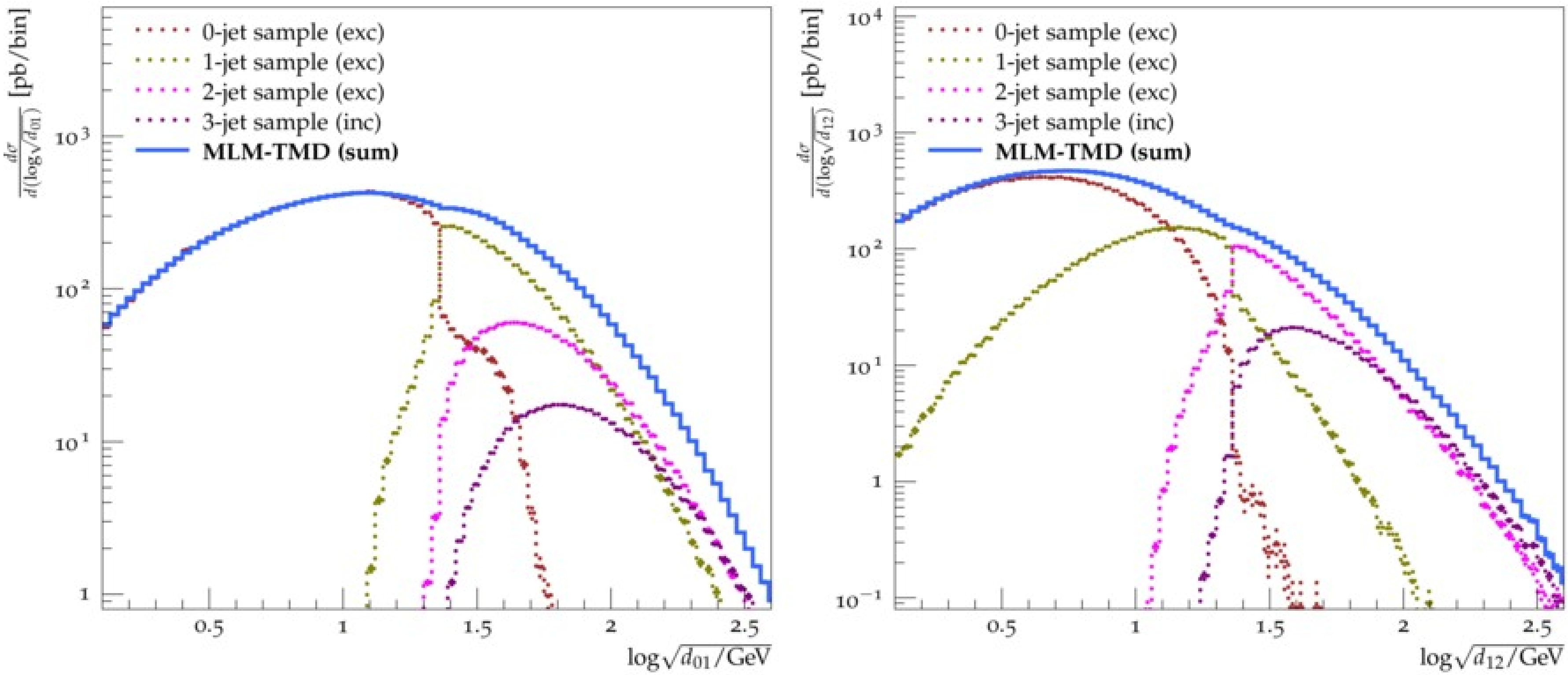


TMD PB evolution decouples from MLM matching

MLM-TMD: Differential Jet Rates

ABM et al. [paper in preparation]

d(n,n+1): scale at which (n+1)-jet configuration becomes n-jet

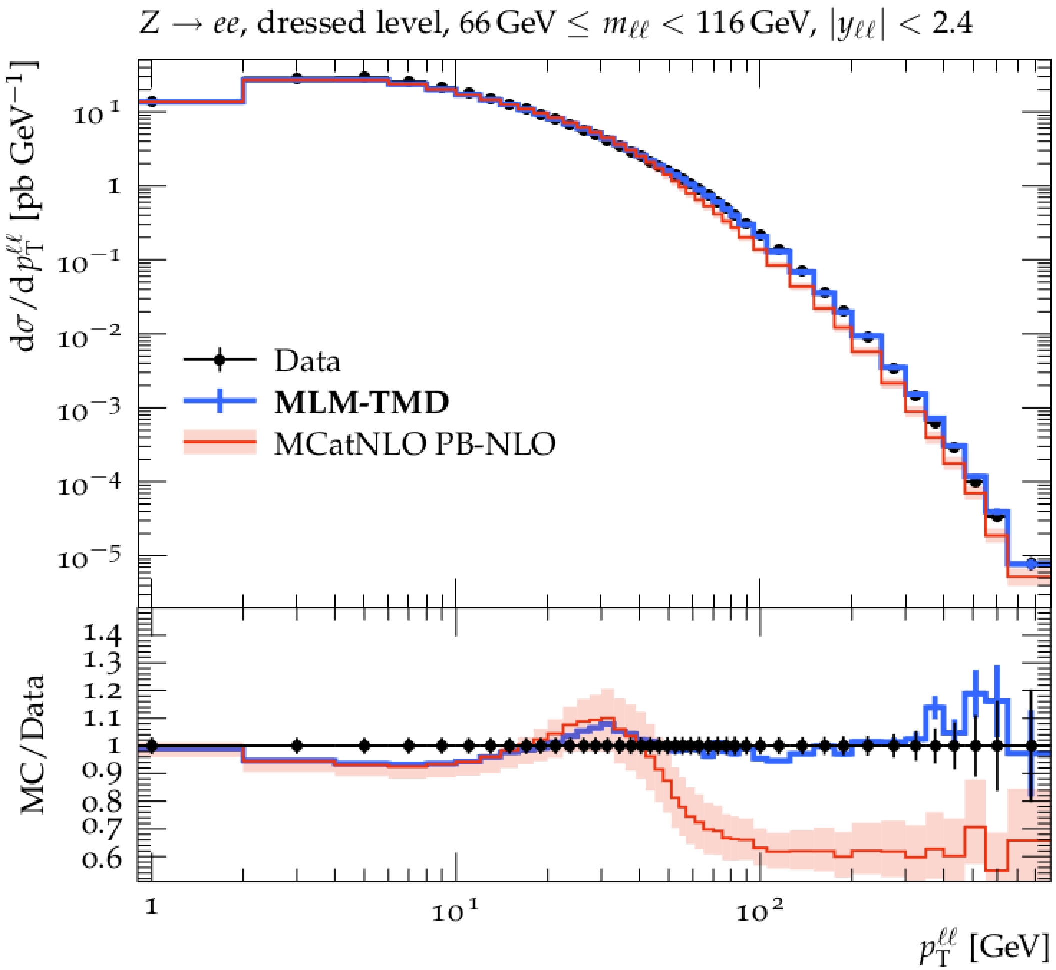


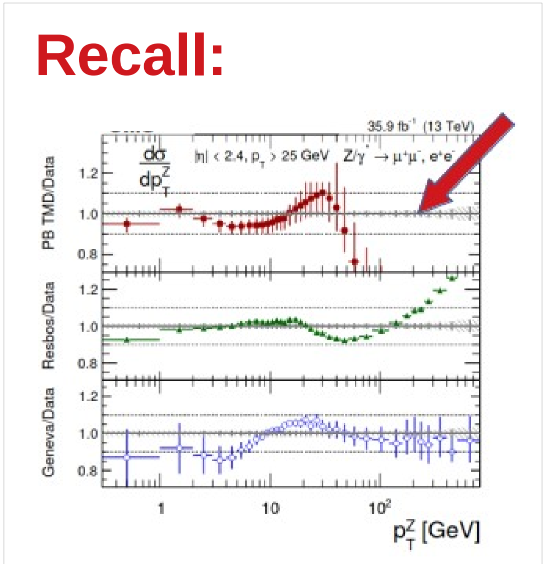
- **Smoothness** → merging follows shower Sudakov suppression
- **Merging scale divides phase space** for different jet multiplicities **avoiding double counting**

MLM-TMD merging method: Results

Z transverse momentum

ATLAS data: [Eur. Phys. J. C 76(5), 1-61 (2016)]



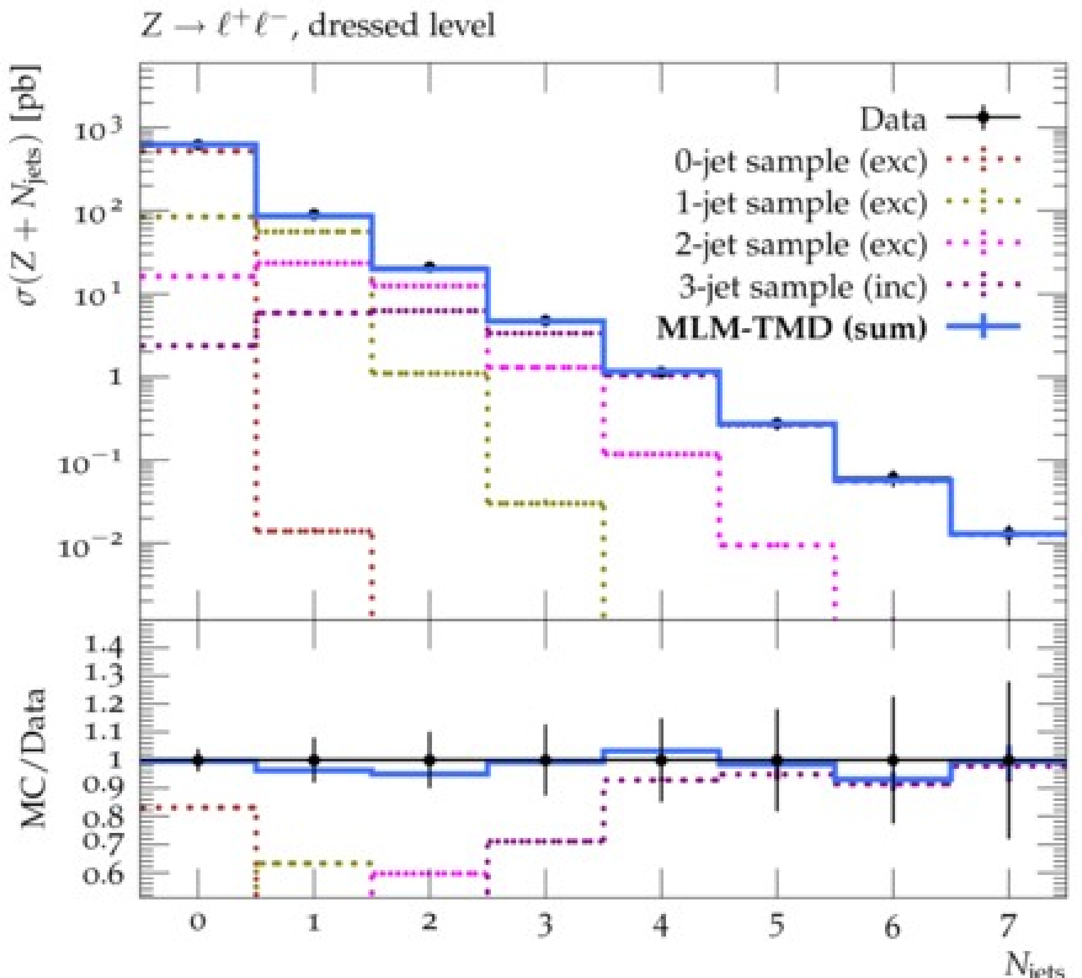


- **Low as well as high-pt** now well described
- Consistent with MCatNLO PB-NLO at low pT

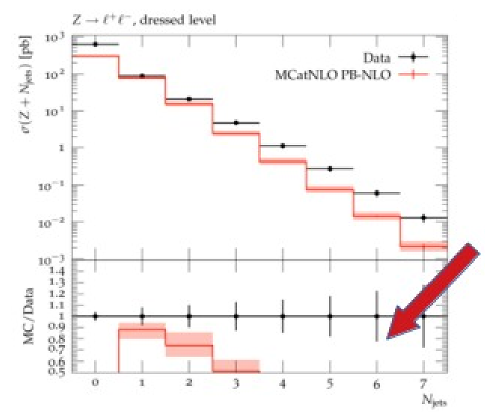
MLM-TMD merging method: Results

Exclusive jet multiplicity in Z events

ATLAS data: [Eur. Phys. J. C77 (2017) 361]



Recall:

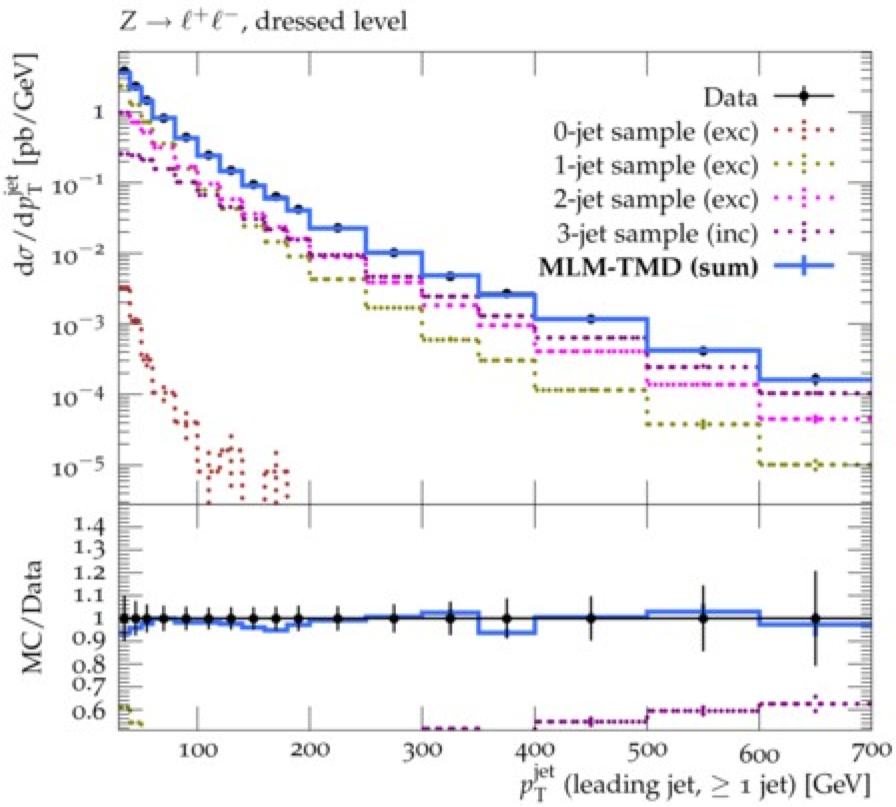


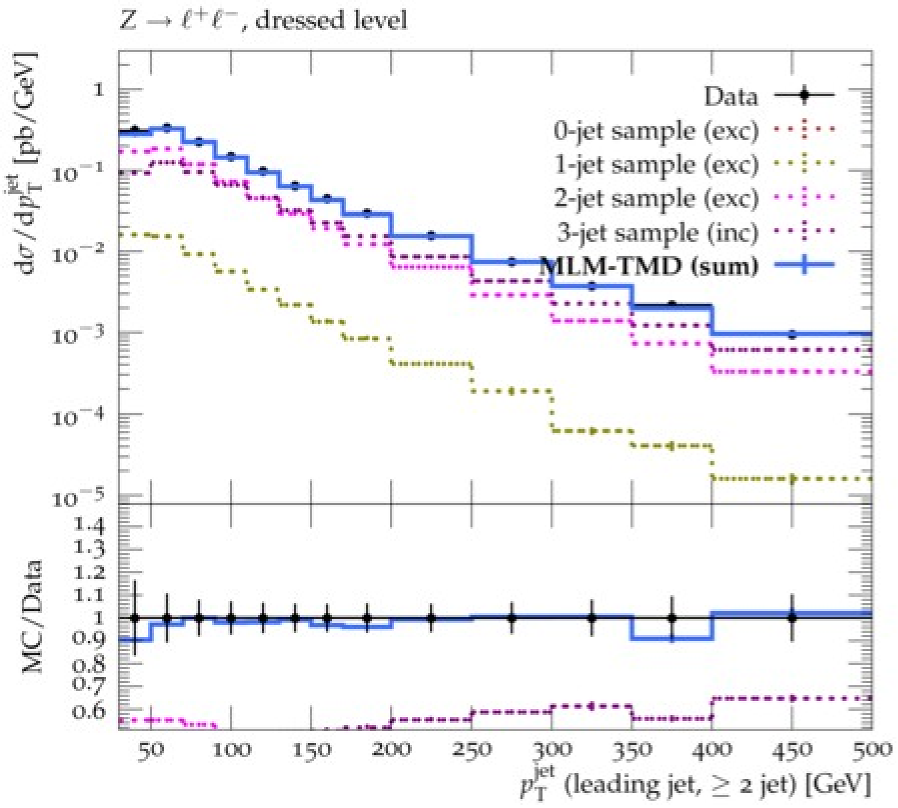
- **Not only the overall recoil but also the number of jets are described**

MLM-TMD merging method: Results

pT of leading jet in Z events

ATLAS data: [Eur. Phys. J. C77 (2017) 361]





- **Fine combination of jet samples** gives a very good description of the jet pT

MLM-TMD merging method: Systematics

Multi-jet cross sections

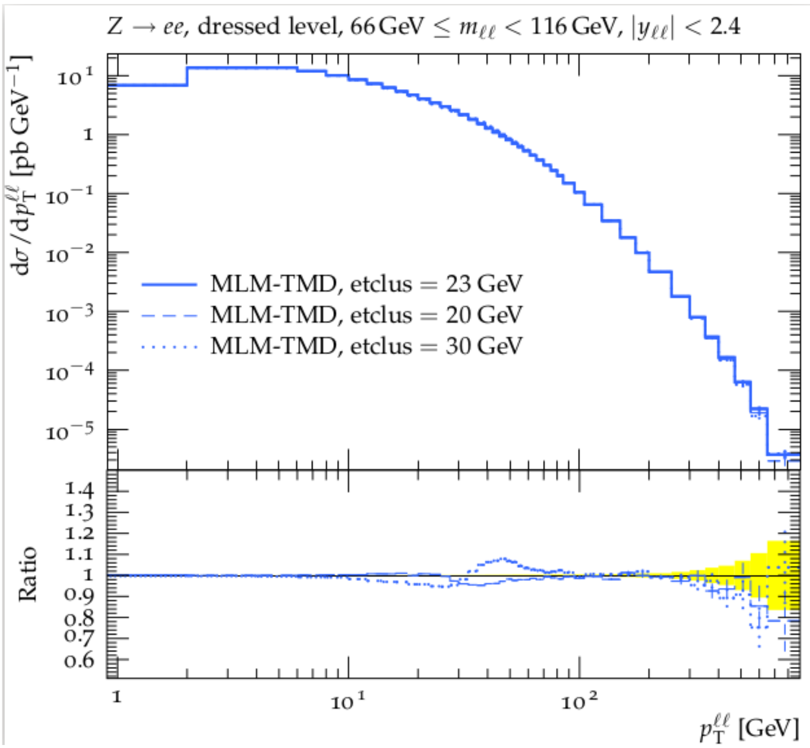
Merging scale [GeV]	σ[tot] [pb]	σ[≥ 1 jet] [pb]	σ[≥ 2 jet] [pb]	σ[≥ 3 jet] [pb]	σ[≥ 4 jet] [pb]
23	1145.95	174.51	40.53	9.67	2.36
33	1126.07	172.30	40.95	9.72	2.38

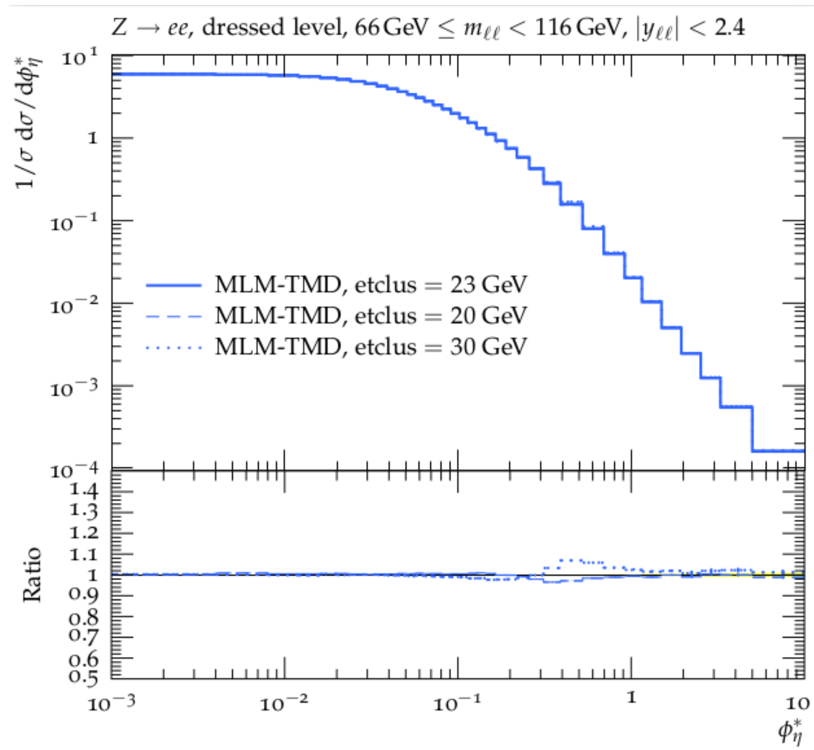
- 10 GeV variation gives **< 2% change** in jets cross sections
- Standard merging algorithms can give over 10 % change for the same variation of the merging scale CF: J. Alwall et al. [EPJC 53, 473–500 (2008)]

→ Dependence on merging scale reduced by treating transverse momentum in the initial state

Systematics

Z pt and phi*

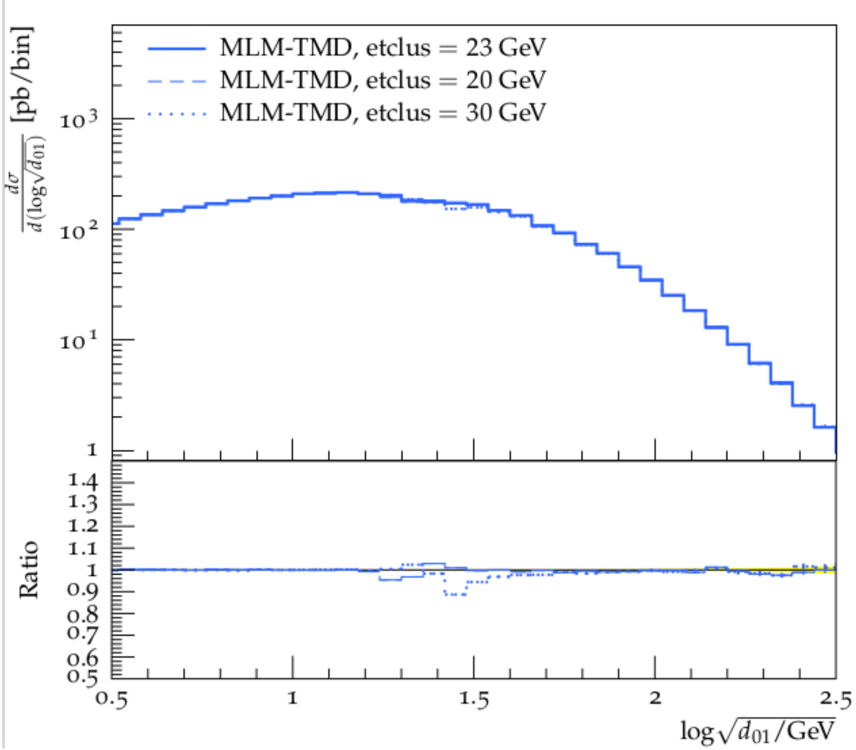


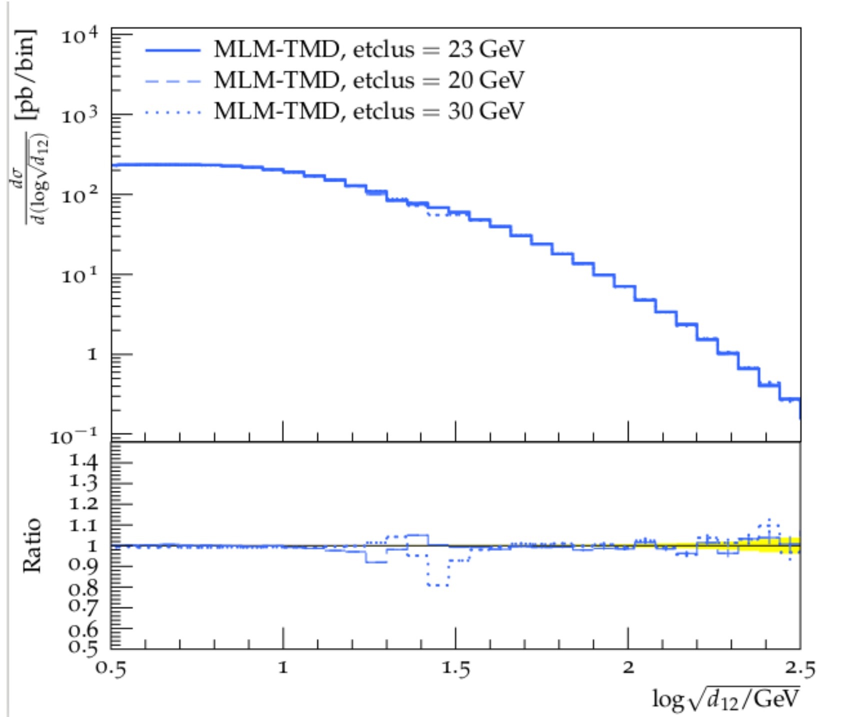


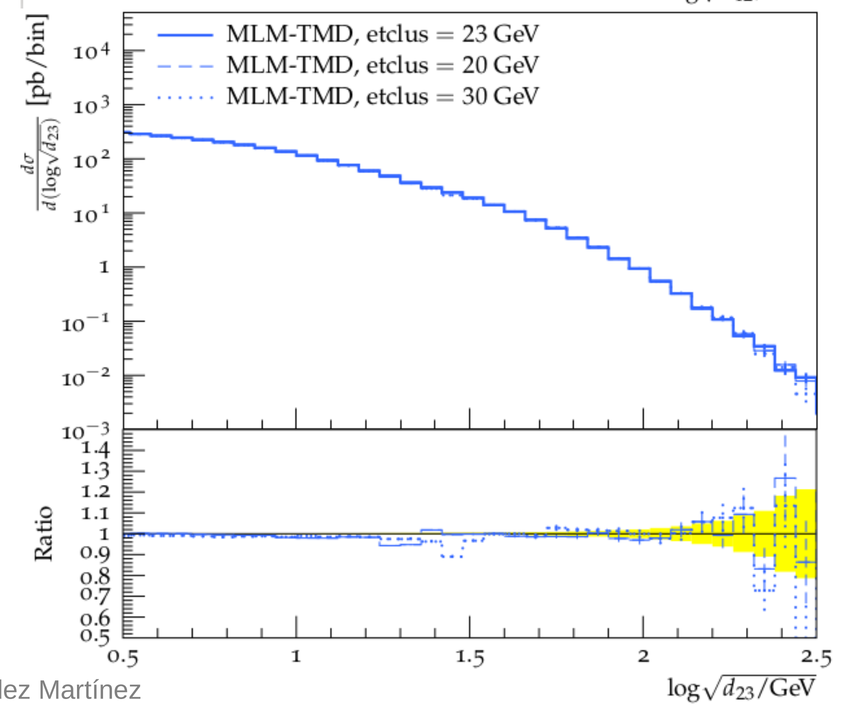
Less than 10% effect localized around the merging scale

Systematics

Differential jet rates



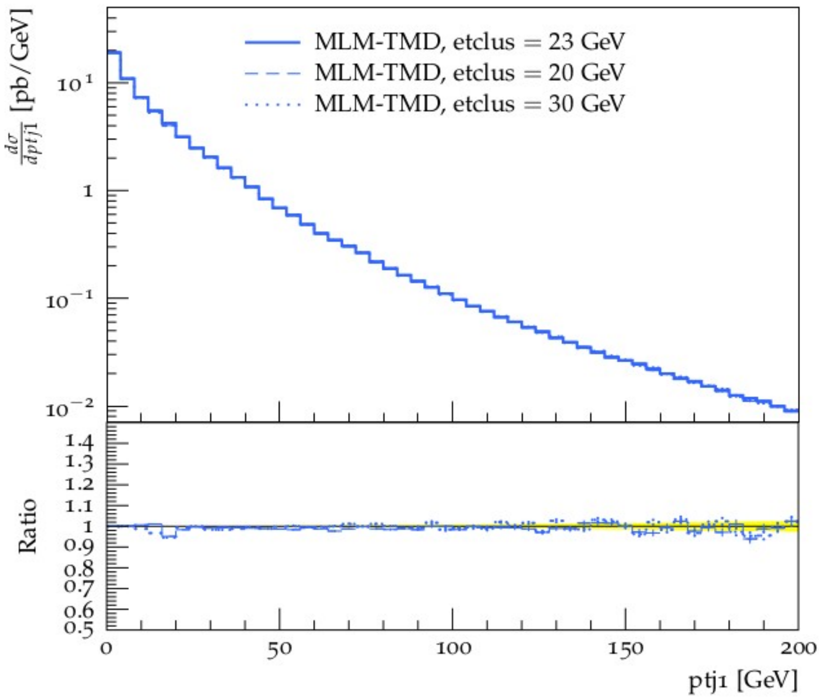


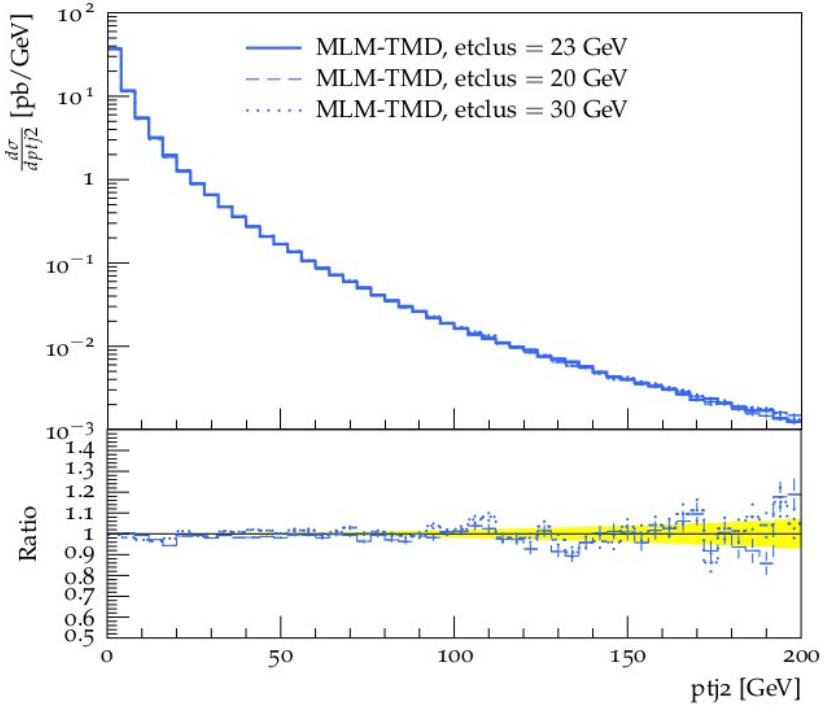


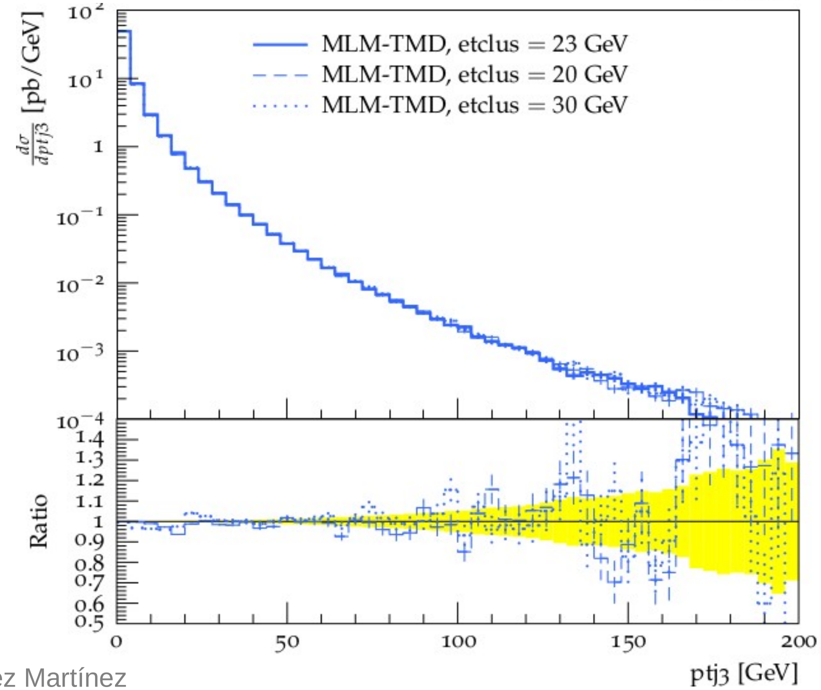
Up to 20% effect localized around the merging scale

Systematics

Pt of the jets







Less than 10% effect localized around the merging scale

Conclusions

- Multiple jet multiplicities evolved with the TMD PB method have been successfully merged with the new MLM-MLM method
- DJR plots are smooth implying a merging Sudakov suppression that follows the shower
- MLM-TMD prediction for Z pT spectrum reproduces the data in the whole range, and it is consistent with PB-MCatNLO
- Merged predictions for jet multiplicity and jet pT agree very well with the data
- Dependency of the MLM-TMD results on the merging scale are of the order or smaller than that of standard algorithms

Thank you