

TMD Evolution and Multi-Jet Merging

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A. Bermúdez Martínez

in collaboration with F. Hautmann and M. Mangano

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 k_t and evolution

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**

FH et al. [[PLB 772 \(2017\) 446–451](#)]

FH et al. [[JHEP 2018, 70 \(2018\)](#)]

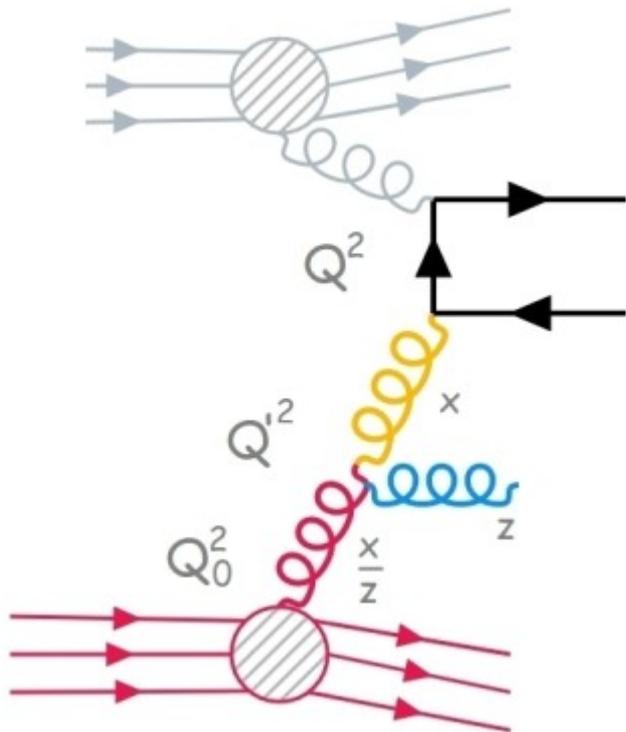
ABM et al. [[PRD 99, 074008 \(2019\)](#)]

 consistently treats perturbative and non-perturbative transverse momentum effects

PB method

PB iterative solution:

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



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

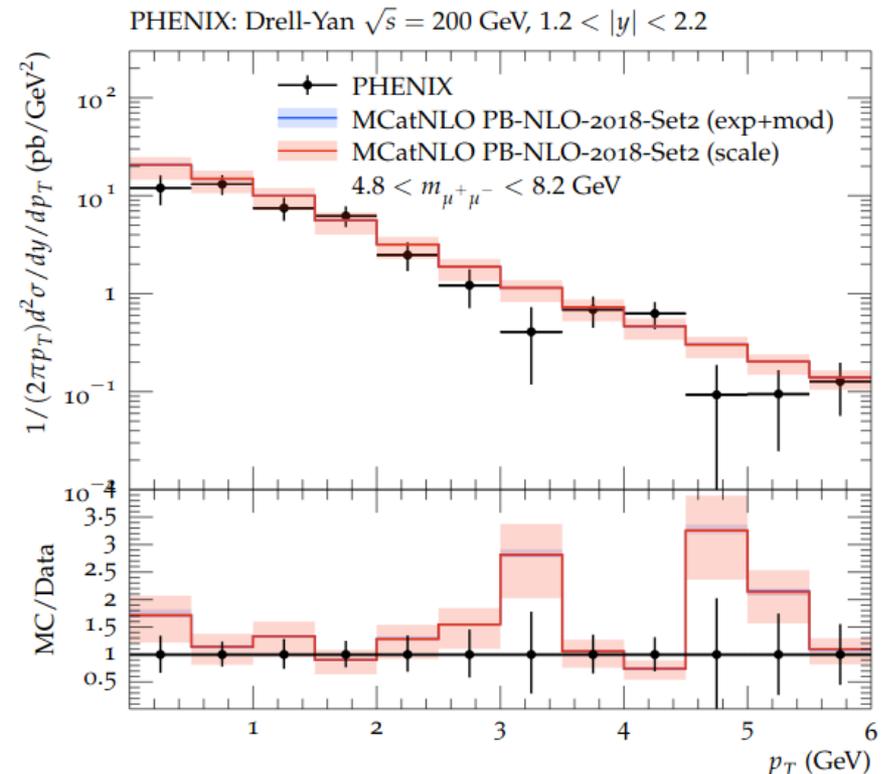
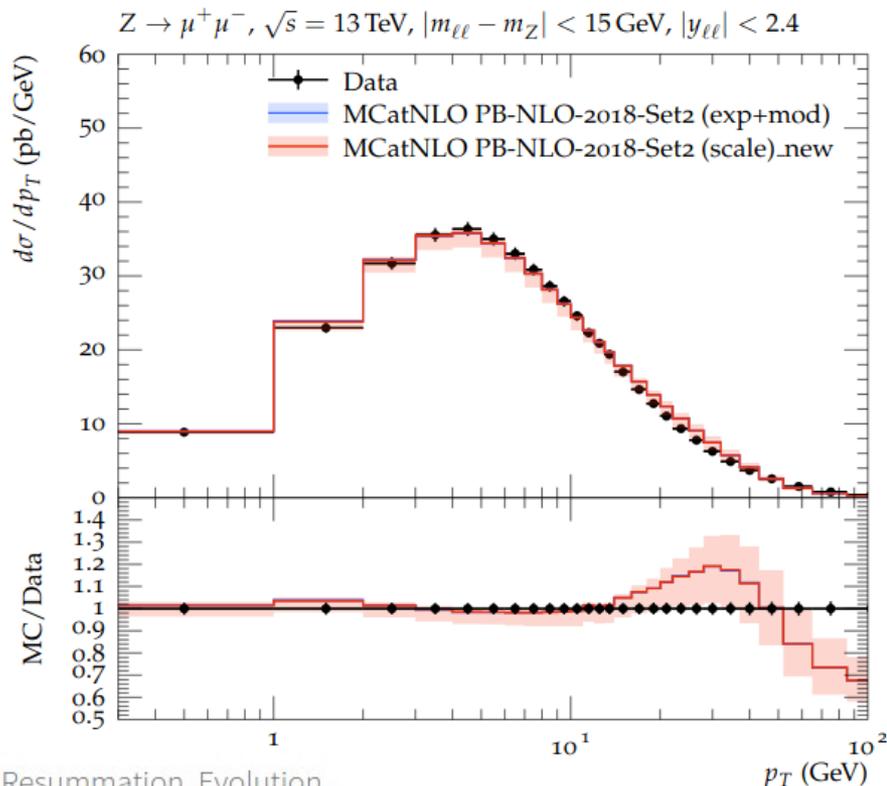
PB method

Achievements

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

ABM et al. [[PRD 100, 074027 \(2019\)](#)]

ABM et al. [[EPJC 80, 598 \(2020\)](#)]

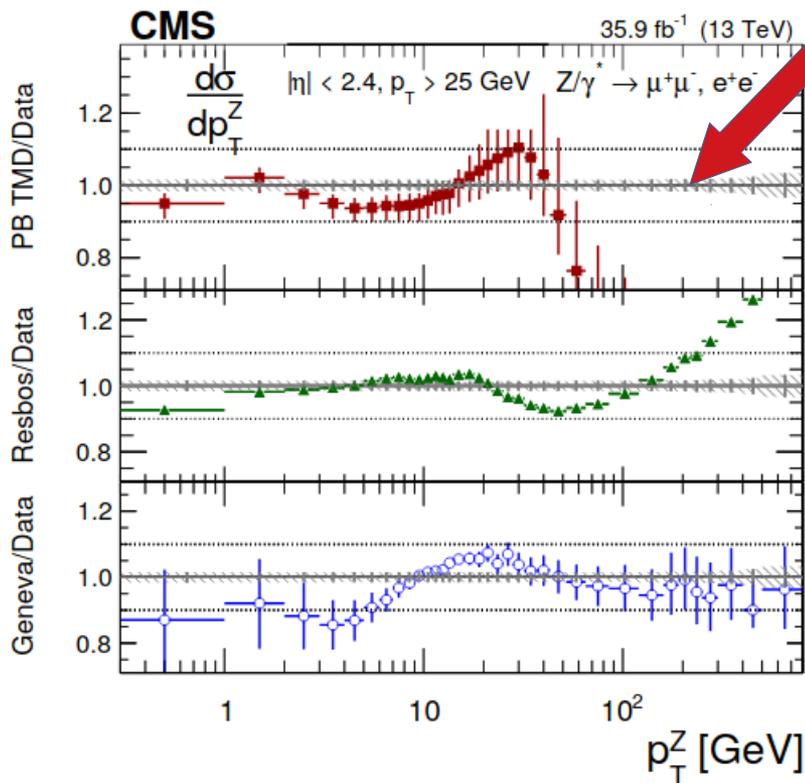


PB method

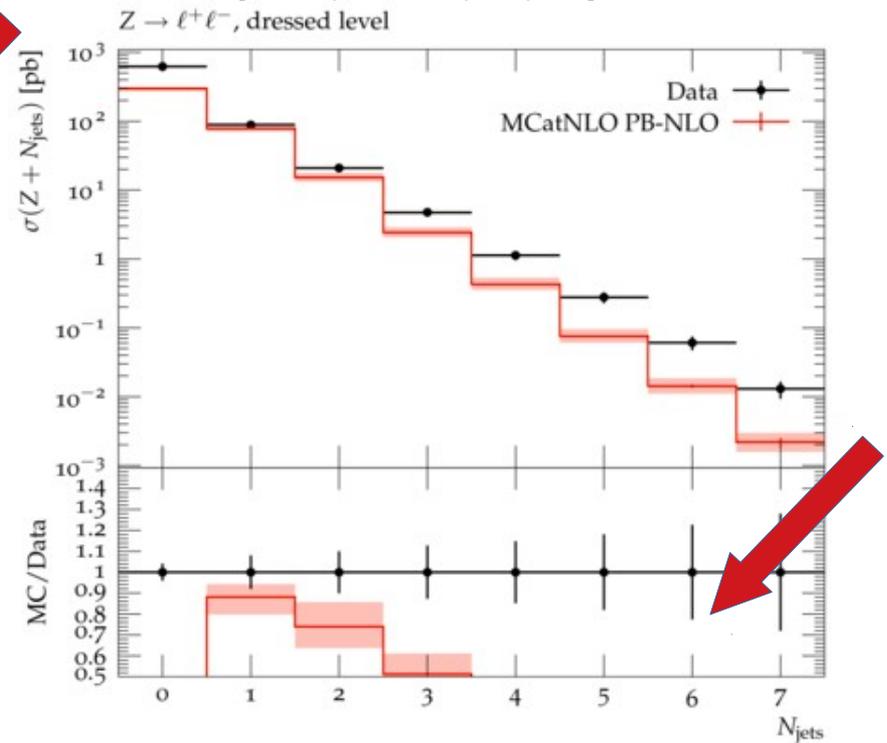
However

- Both high p_T 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]



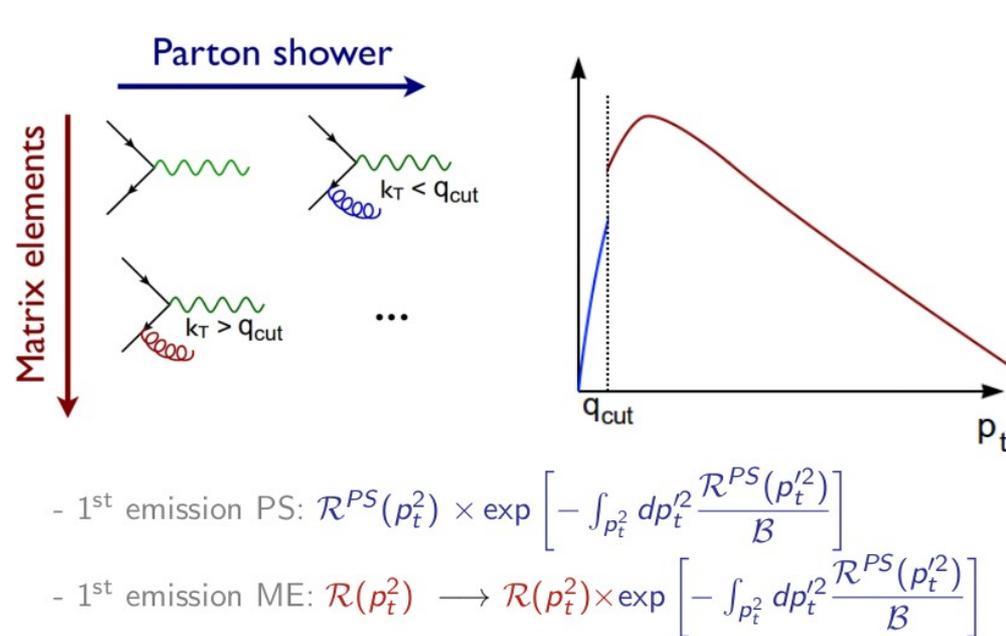
What we want:

- 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

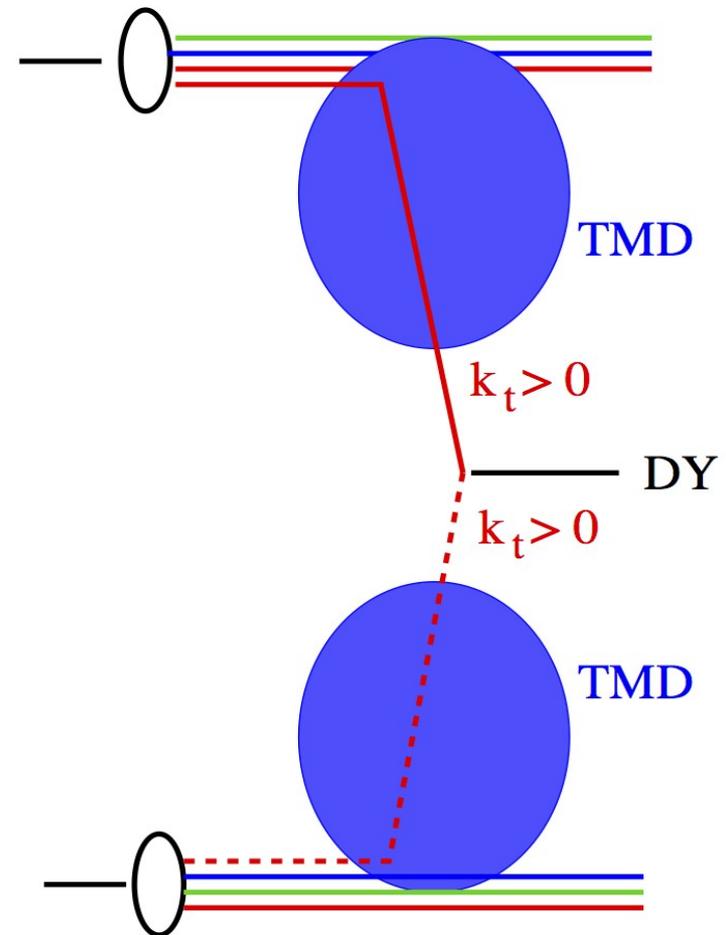
- Make higher-order ME exclusive by Sudakov suppression
 - Avoid double counting between PS and ME
- ↓
- Improvement of hard, wide-angle emissions
 - Description of high- p_T phenomena



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



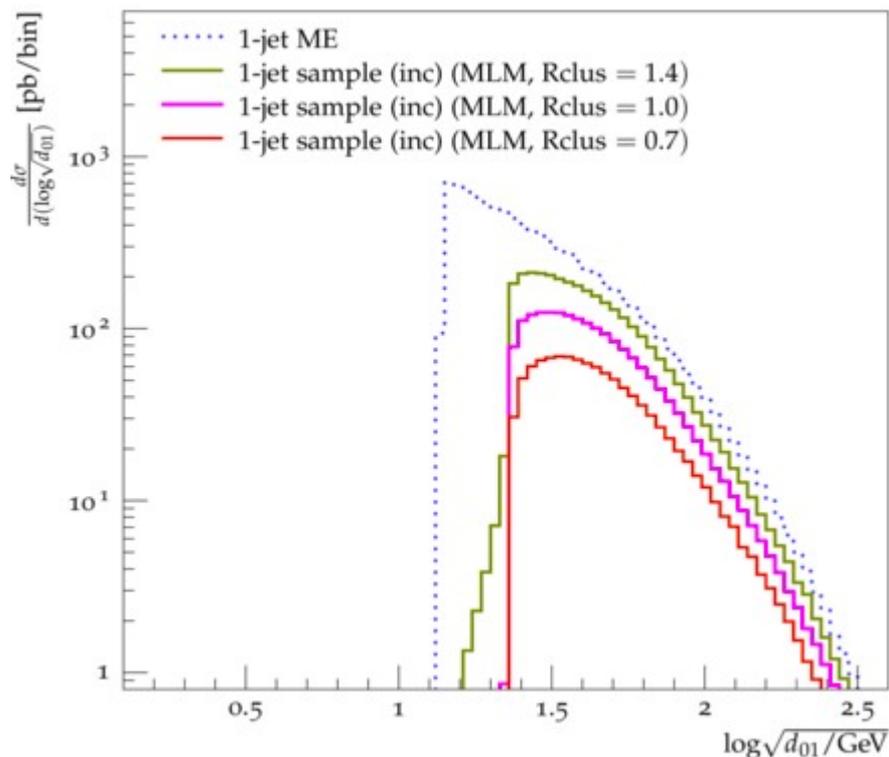
New merging procedure applicable to TMDs!

From MLM to MLM-TMD

ABM et al. [paper in preparation]

What about the original MLM applied to TMD events?

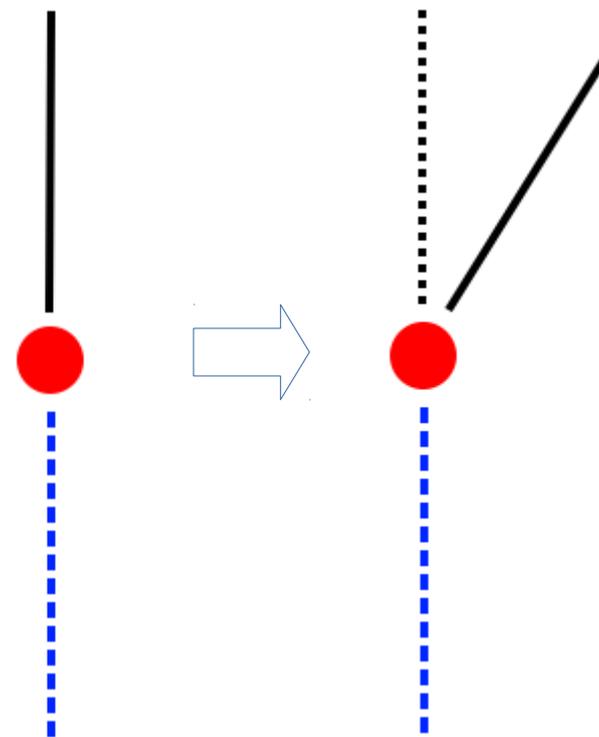
- very strong dependence on R_{clus}
- **at large scales ME accuracy lost!**



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

at ME level

after shower

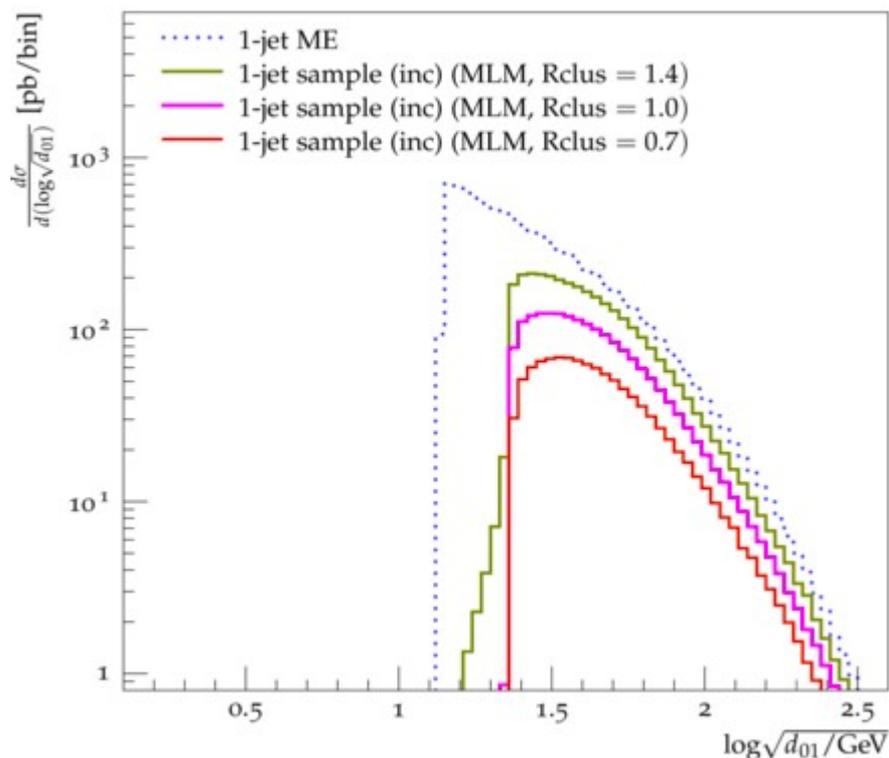


From MLM to MLM-TMD

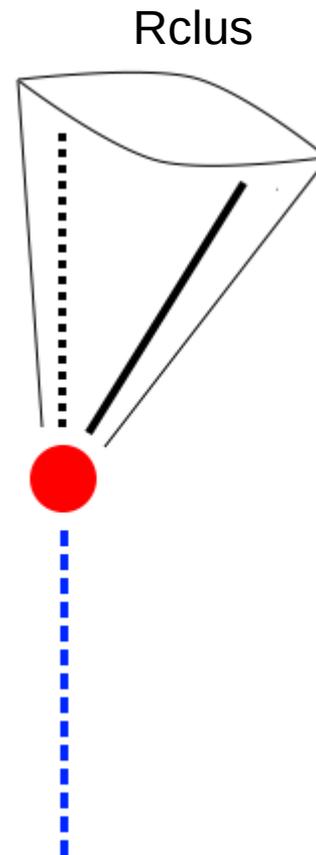
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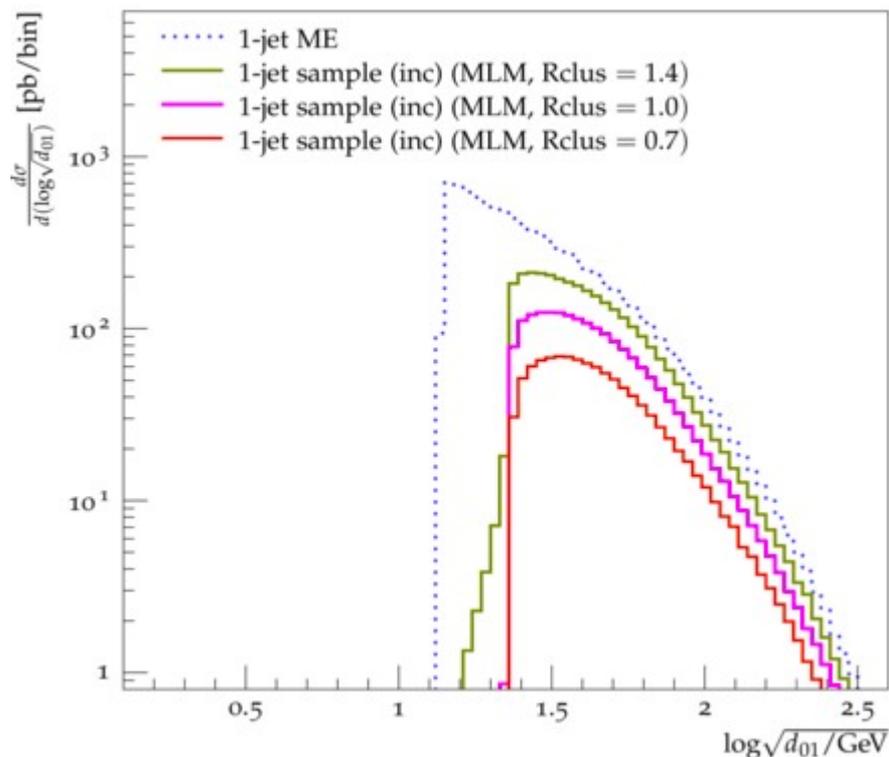
reject non-matched events

From MLM to MLM-TMD

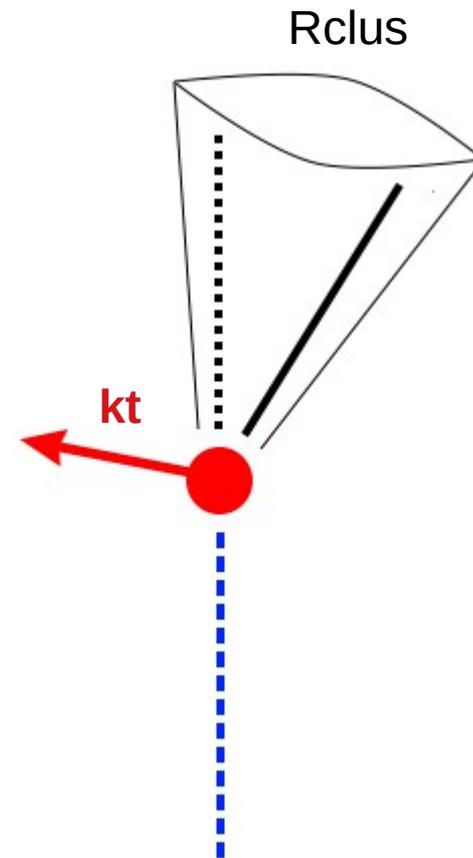
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$d(n, n+1)$: square of scale at which $(n+1)$ -jet configuration becomes n -jet



$$kt_{\text{max}} = kt_{\text{max}}(R_{\text{clus}}) !$$

R_{clus} translates into a maximum TMD evolution scale

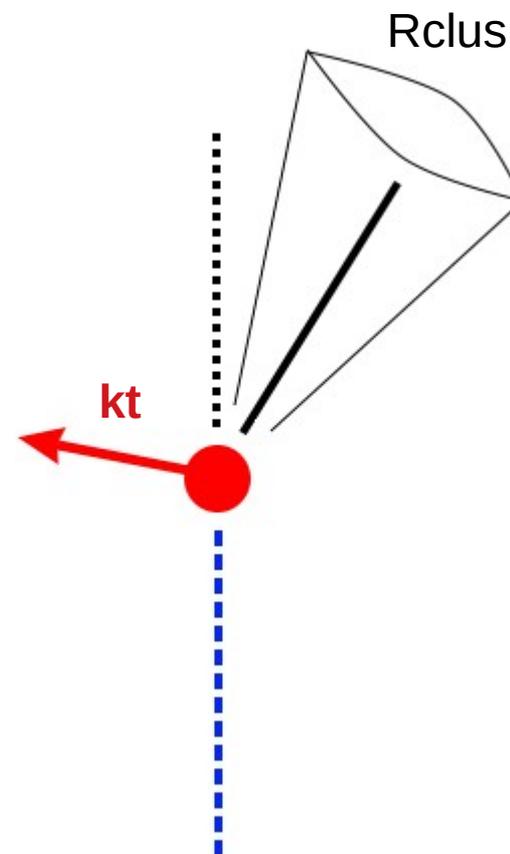
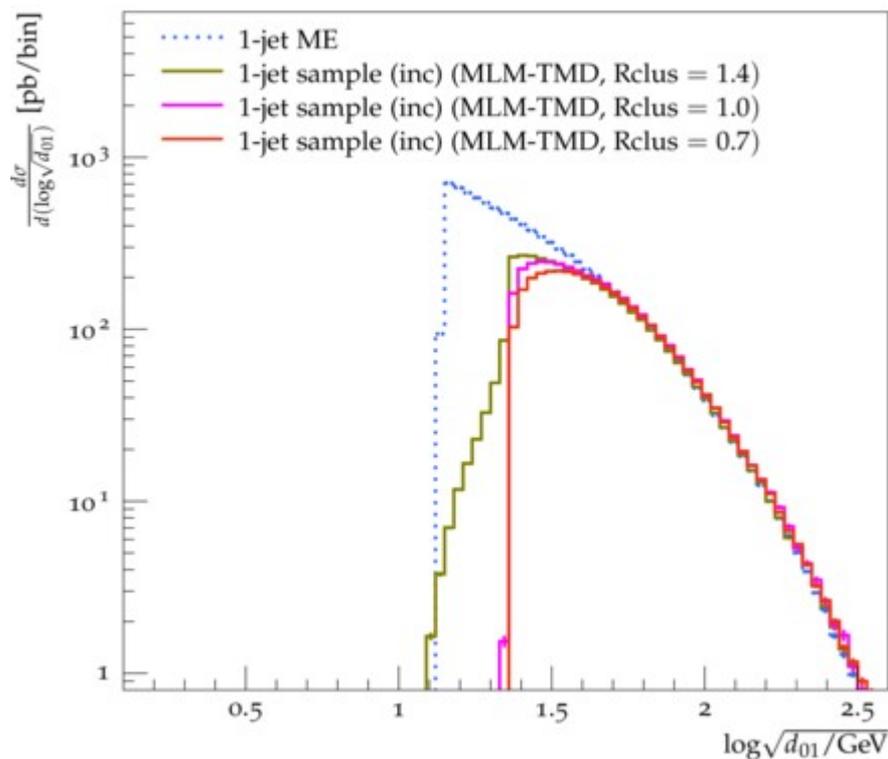
⇒ original MLM incompatible with PB TMD evolution

From MLM to MLM-TMD

ABM et al. [paper in preparation]

MLM-TMD

- little dependence on R_{clus}
- at large scales ME accuracy recovered!

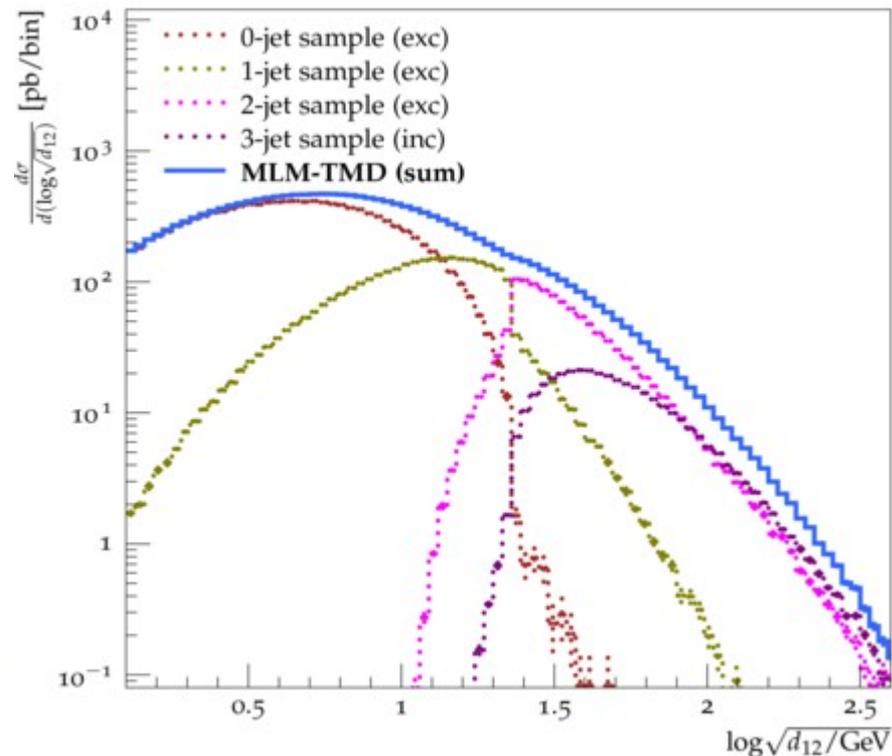
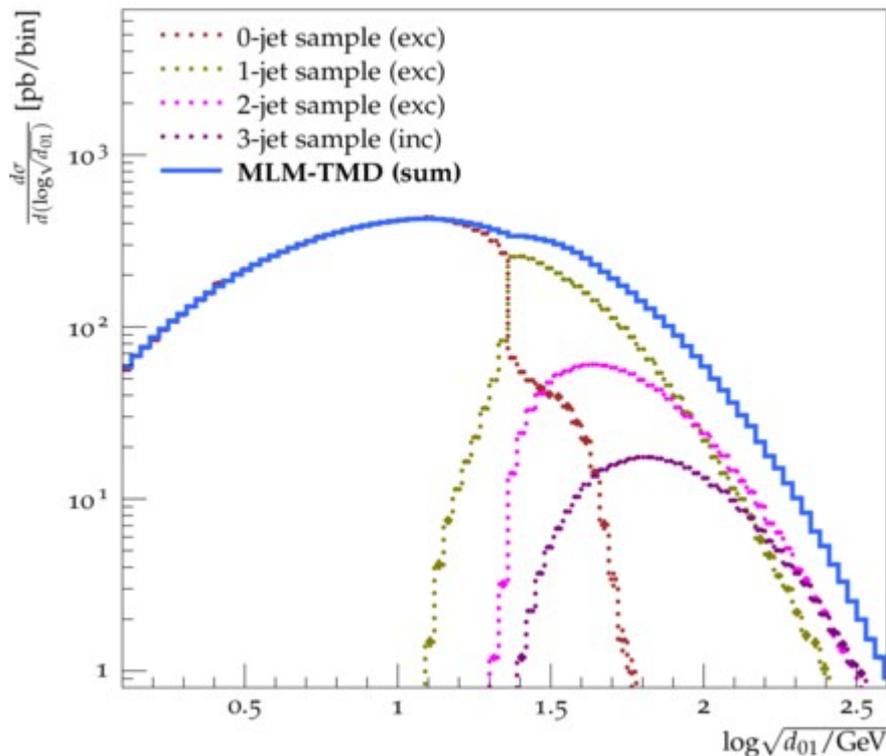


⇒ TMD PB evolution decouples from MLM matching

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



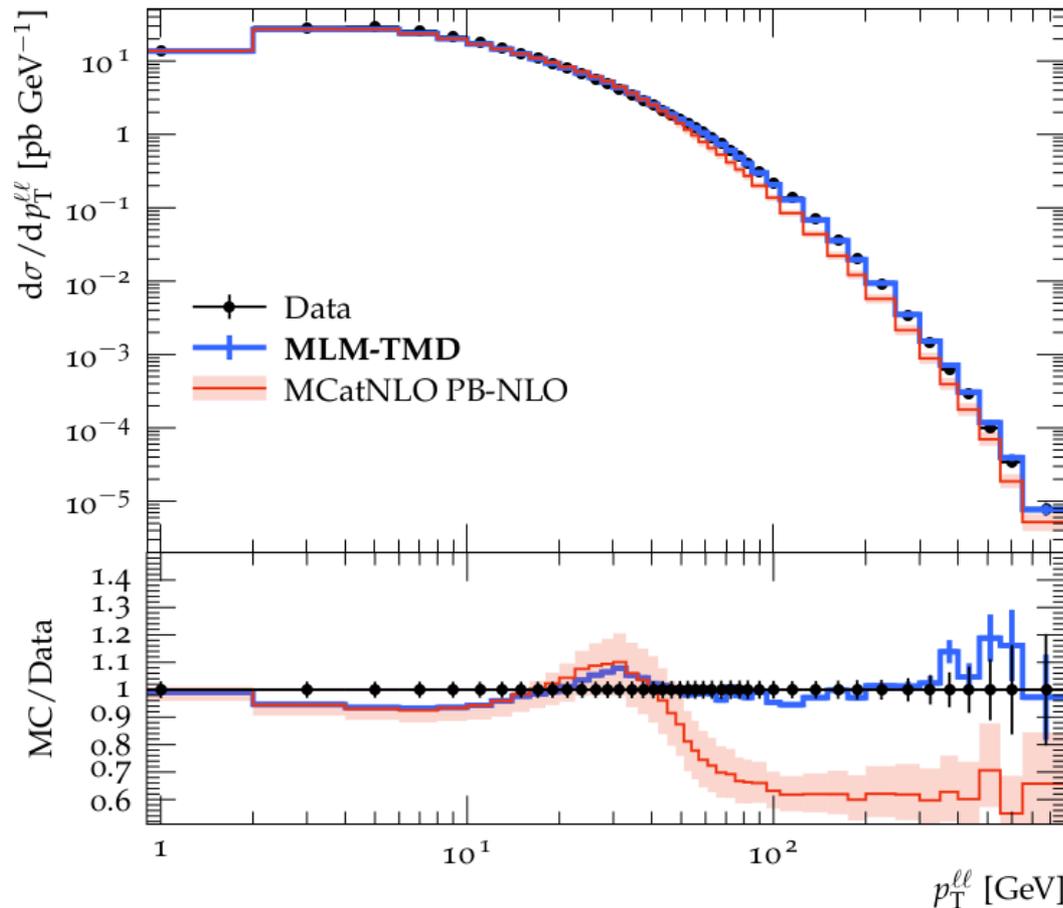
- **Smoothness** \longrightarrow merging follows shower Sudakov suppression
- **Merging scale divides phase space** for different jet multiplicities **avoiding double counting**

MLM-TMD merging method: Results

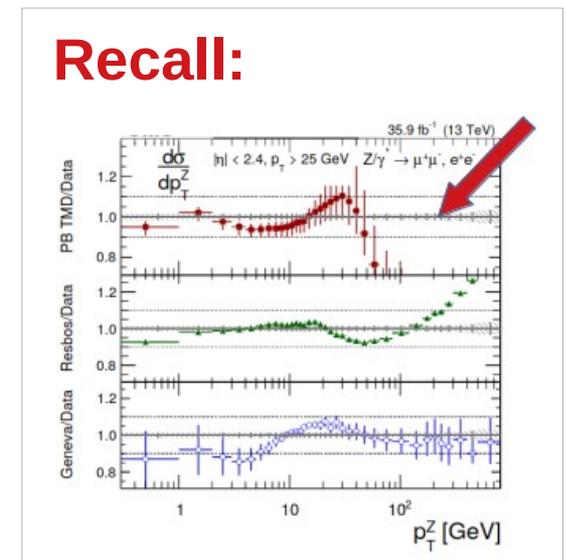
Z transverse momentum

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

$Z \rightarrow ee$, dressed level, $66 \text{ GeV} \leq m_{\ell\ell} < 116 \text{ GeV}$, $|y_{\ell\ell}| < 2.4$



Recall:

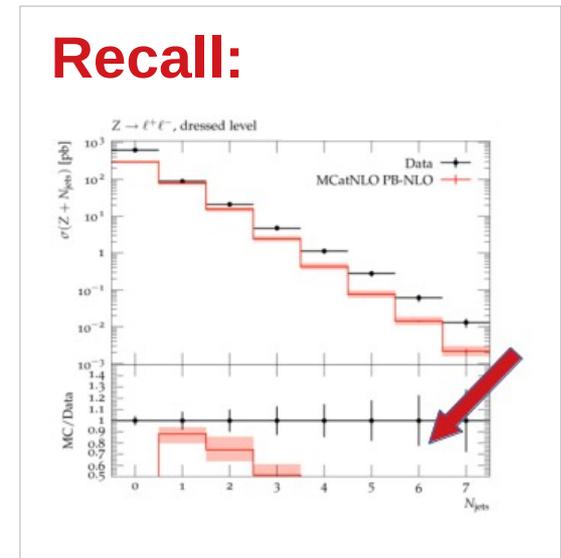
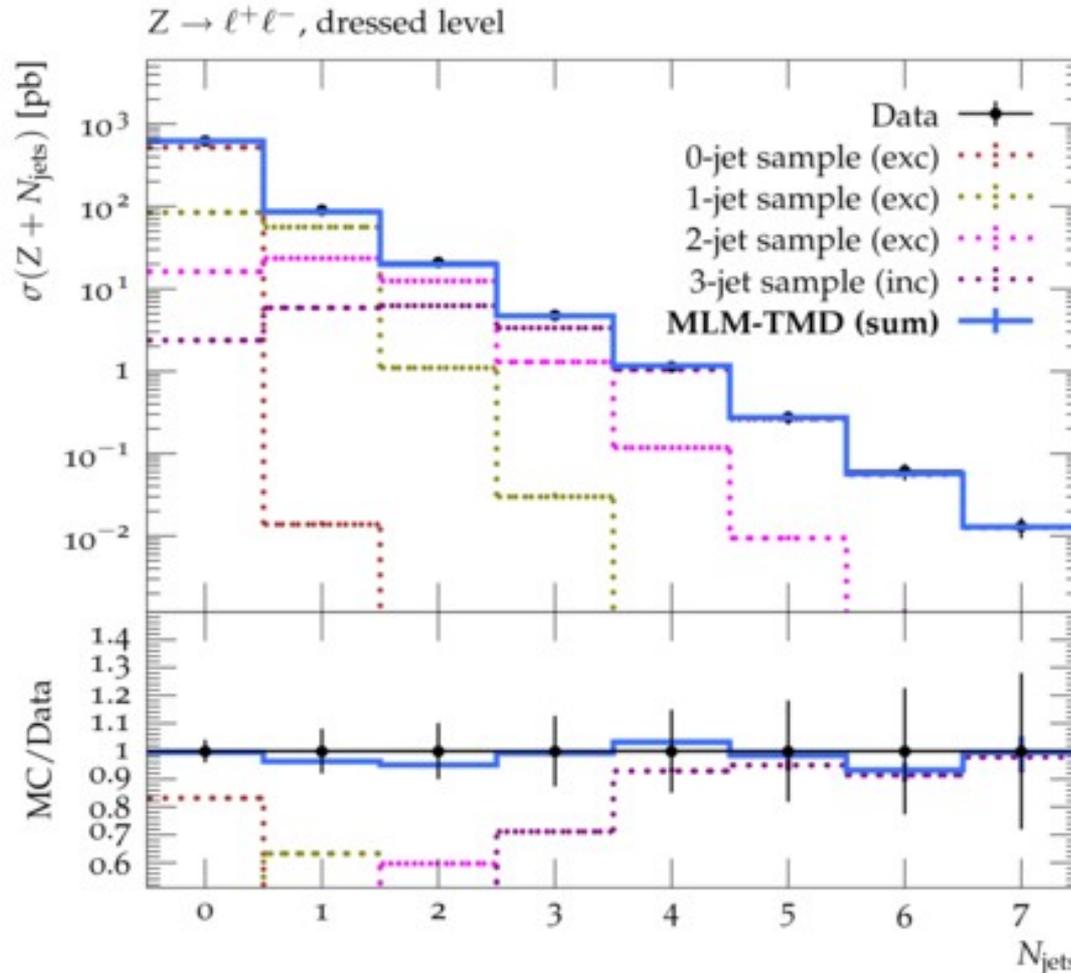


- Low as well as high-pt now well described
- Consistent with MCatNLO PB-NLO at low pT

MLM-TMD merging method: Results

Exclusive jet multiplicity in Z events

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

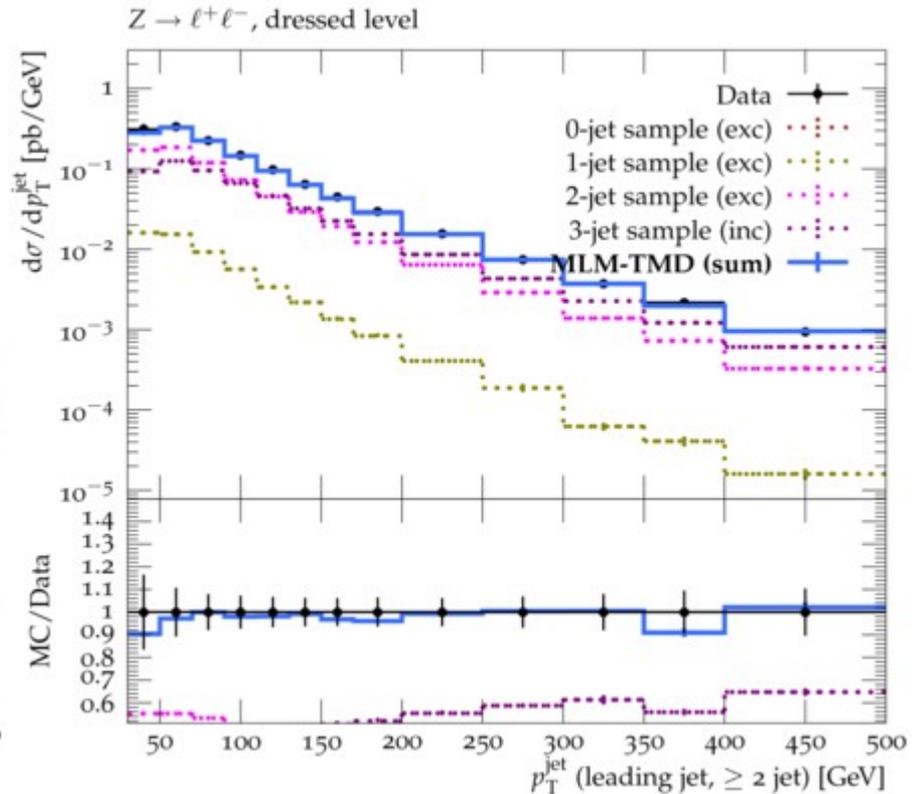
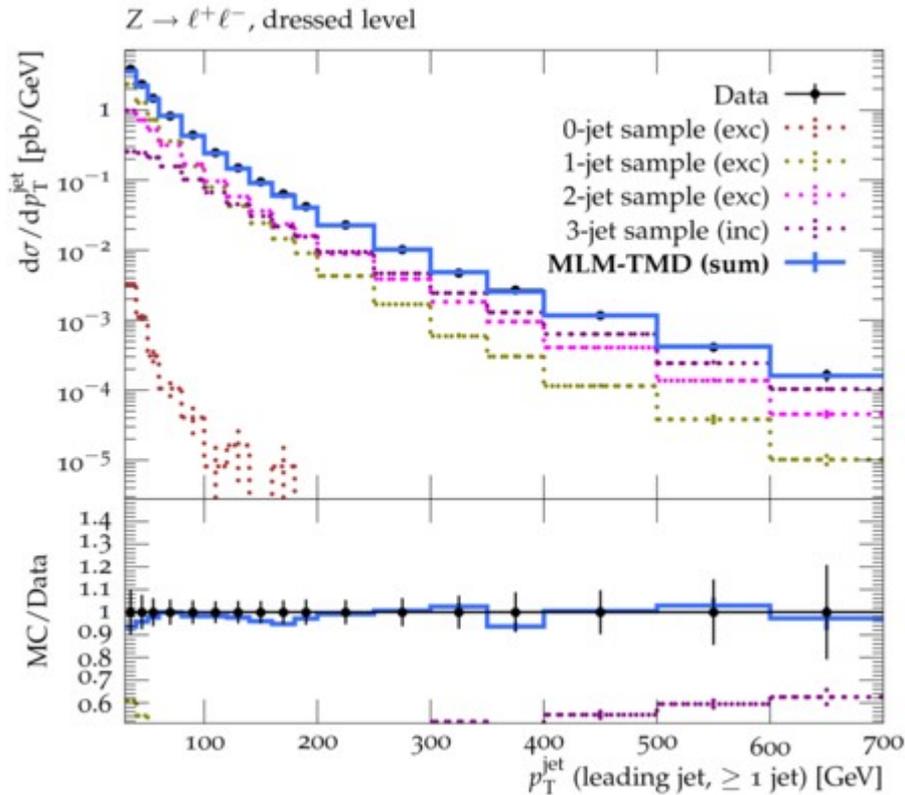


- Not only the overall recoil but also the number of jets are described

MLM-TMD merging method: Results

p_T 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 p_T

MLM-TMD merging method: Systematics

Multi-jet cross sections

| Merging scale [GeV] | $\sigma[\text{tot}]$ [pb] | $\sigma[\geq 1 \text{ jet}]$ [pb] | $\sigma[\geq 2 \text{ jet}]$ [pb] | $\sigma[\geq 3 \text{ jet}]$ [pb] | $\sigma[\geq 4 \text{ jet}]$ [pb] |
|---------------------|---------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 23 | 1145.95 | 174.51 | 40.53 | 9.67 | 2.36 |
| 33 | 1126.07 | 172.30 | 40.95 | 9.72 | 2.38 |

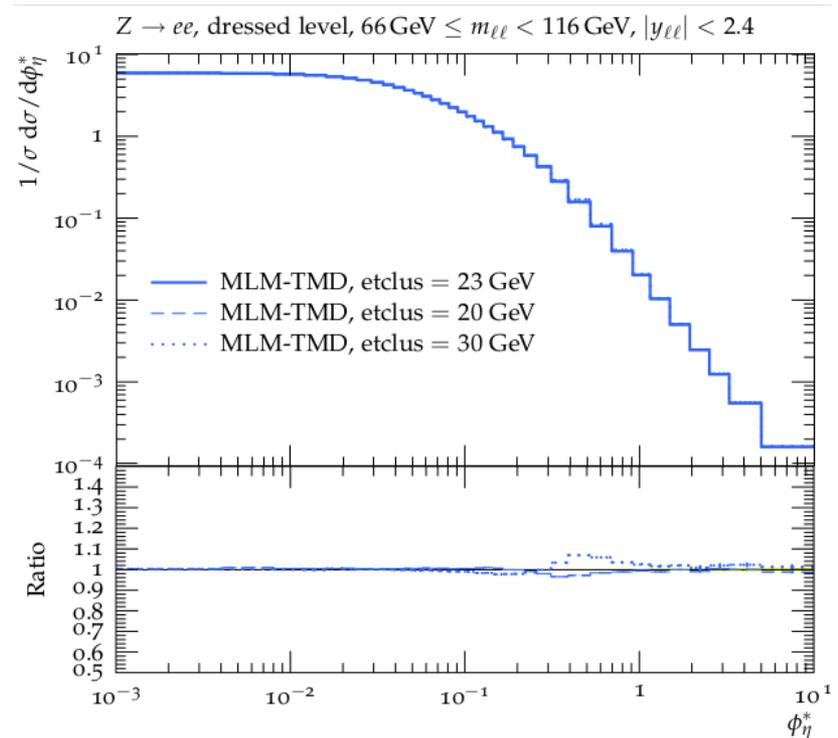
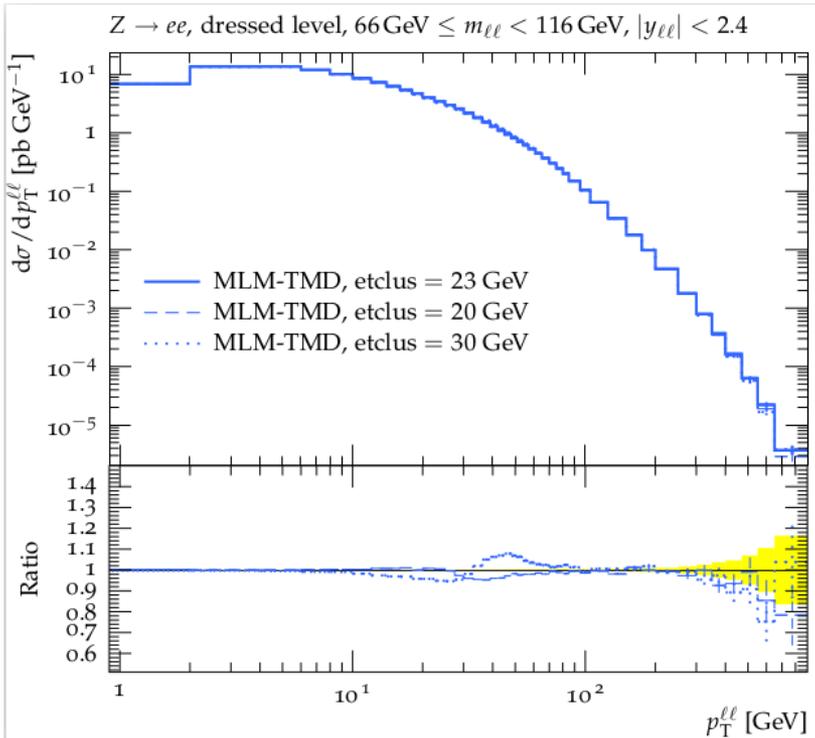
- 10 GeV variation gives **< 2% change** in jets cross sections
- Standard merging algorithms can give over 10 % change for the same variation of the merging scale CF: J. Alwall et al. [EPJC 53, 473–500 (2008)]



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

Systematics

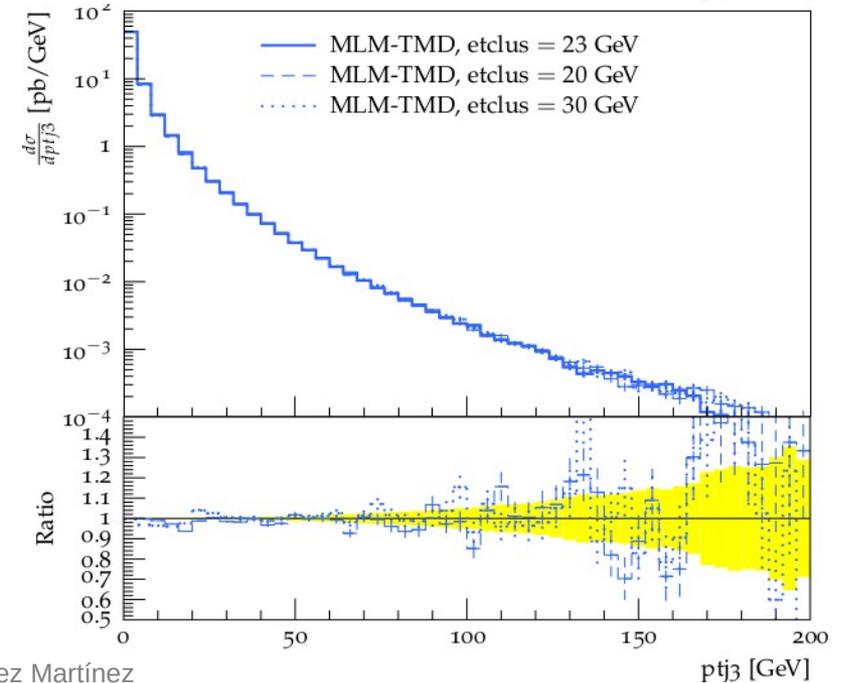
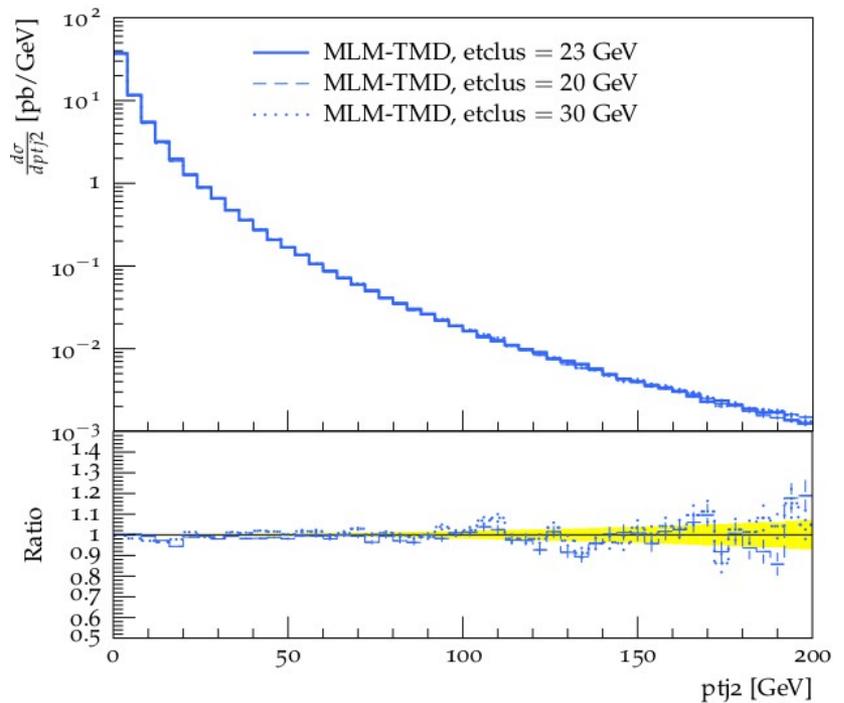
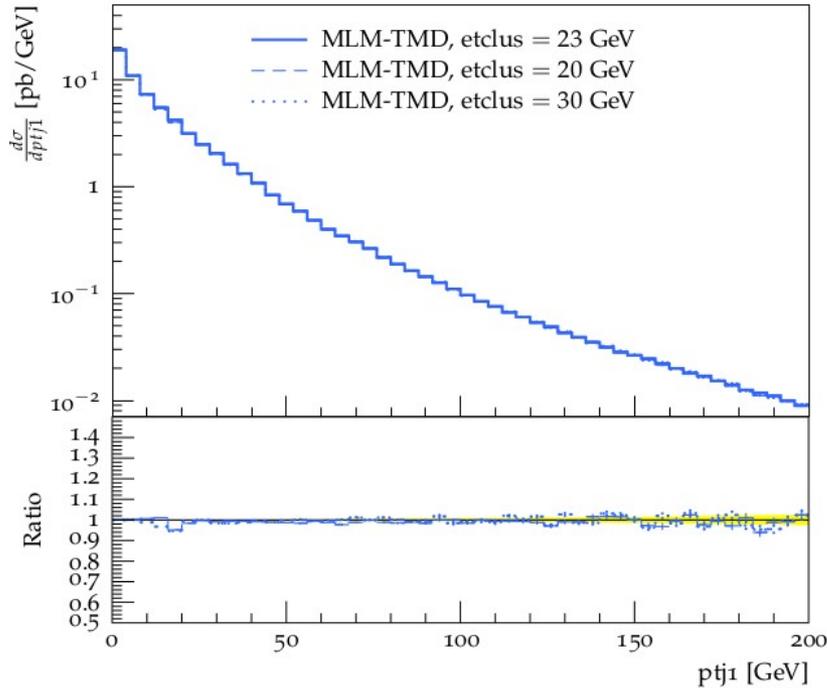
Z pt and phi*



Less than 10% effect localized around the merging scale

Systematics

Pt of the jets



Less than 10% effect localized around the merging scale

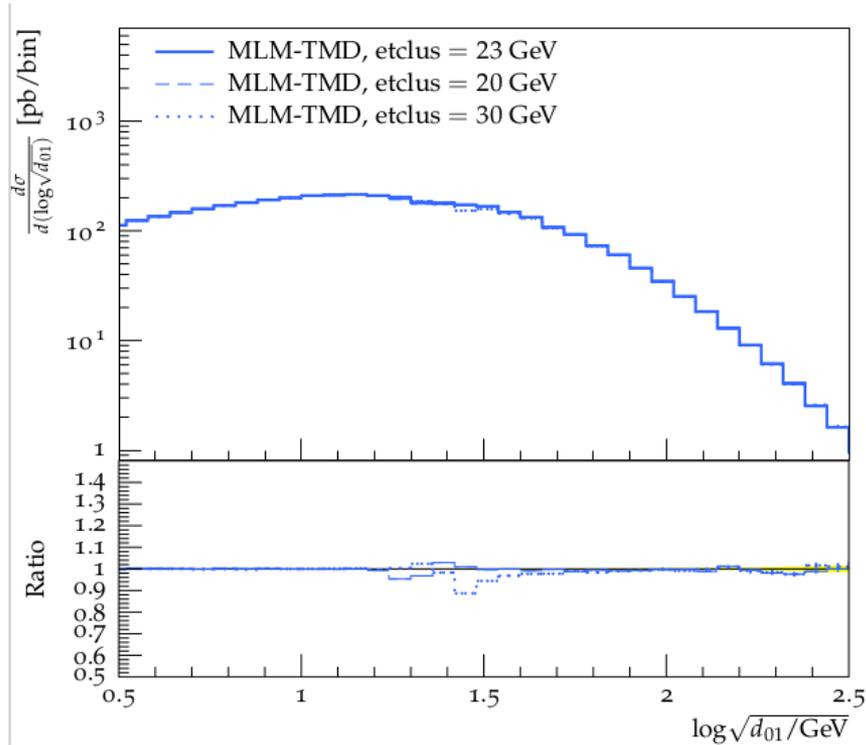
Conclusions

- 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

Systematics

Differential jet rates



Up to 20% effect localized around the merging scale

