Energy scaling of the intrinsic-kT in the Parton Branching Method

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Foreword

- This talk is not a CMS presentation
- This is neither a theory talk
- This is more about an experimentalist's point of view on a challenging topic
    - What do we need experimentally?
    - How we can achieve it using MC techniques
        - How accurate do we want our modeling of the whole spectrum of interest?

Motivation

- Processes involving W or Z/γ* boson productions are one of the best understood processes at hadron colliders
  - W->lnu & Z->ll, (l=e,μ) are among the cleanest final states experimentally
  - Allows probing various QCD effects by studying kinematics precisely
    - Color singlet final-state: probing QCD ISR effects
  - Different kinematics regions probing pQCD as well as npQCD effects

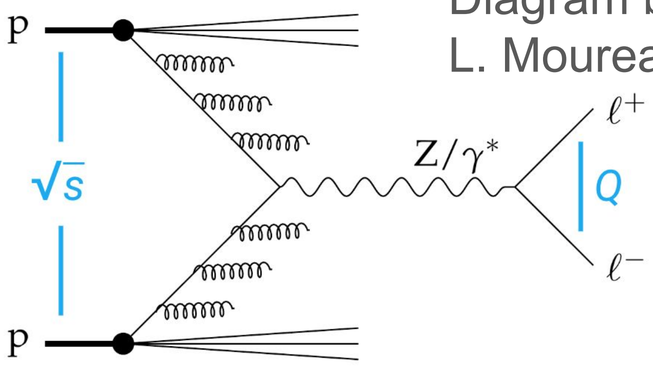
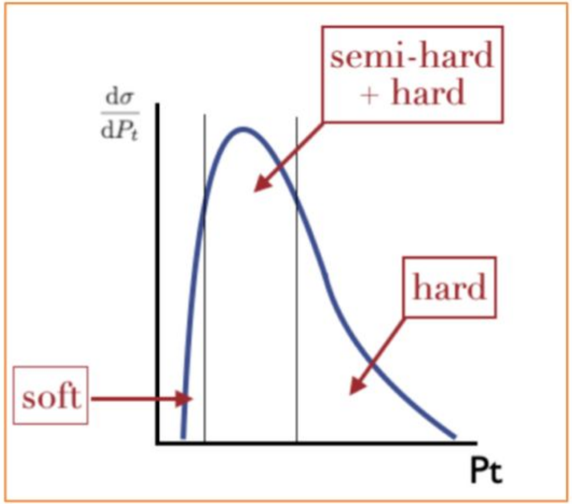
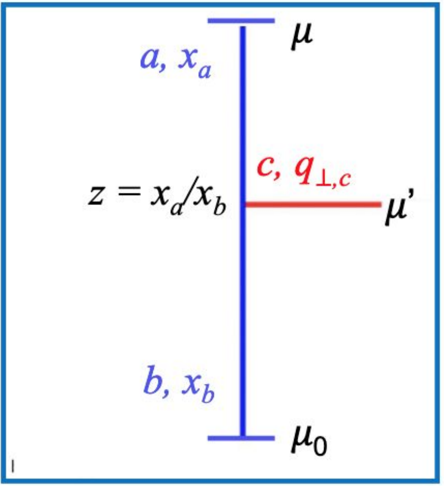


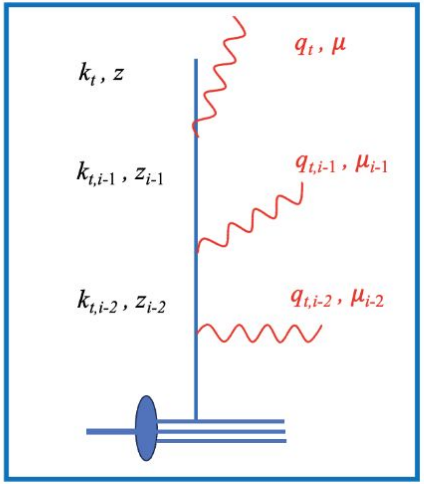
Diagram by L. Moureaux



Illustrations from N.Raičević

PBTMD formalism





- Evolution from a small scale
- Branchings governed by scale evolution
  - Every branching generates some q_T
    - $q_{T,c} \sim \mu' (1-z)$
  - Divided into two regions:
    - a resolvable region, with $0 < z < z_{dyn}$ $(q_T > q_0)$
    - a non-resolvable region with $z_{dyn} < z < z_M$ $(q_T < q_0)$
    - Where $z_{dyn} = 1 - q_0/\mu$.

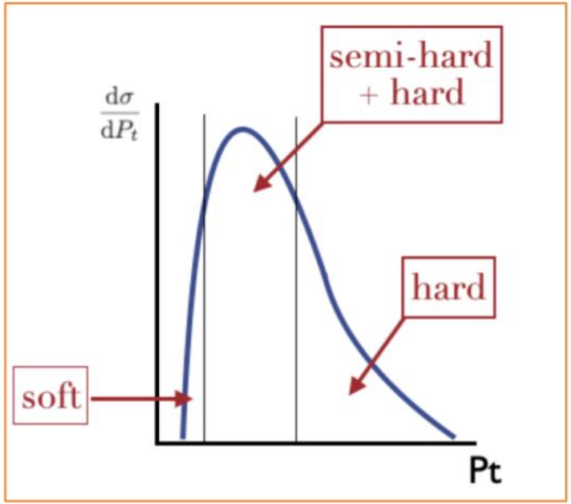
z – longitudinal momentum transfered at the branching ($0 < z < z_M$)

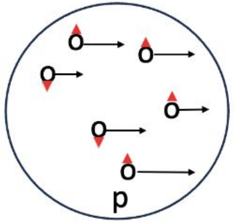
- kT accumulates through repeated parton branchings
  - Using TMD evolution at each branching

$$k_T = k_{T,0} + \sum_c q_{T,c}$$

intrinsic k_T

- Parton k_T distribution at small scale
  - Probing Fermi motion effects of incoming partons
- Present in all formalisms
  - Parton showers as well as analytic resummation methods
- Not calculable by perturbative theory
  - Need to be extracted from experimental results



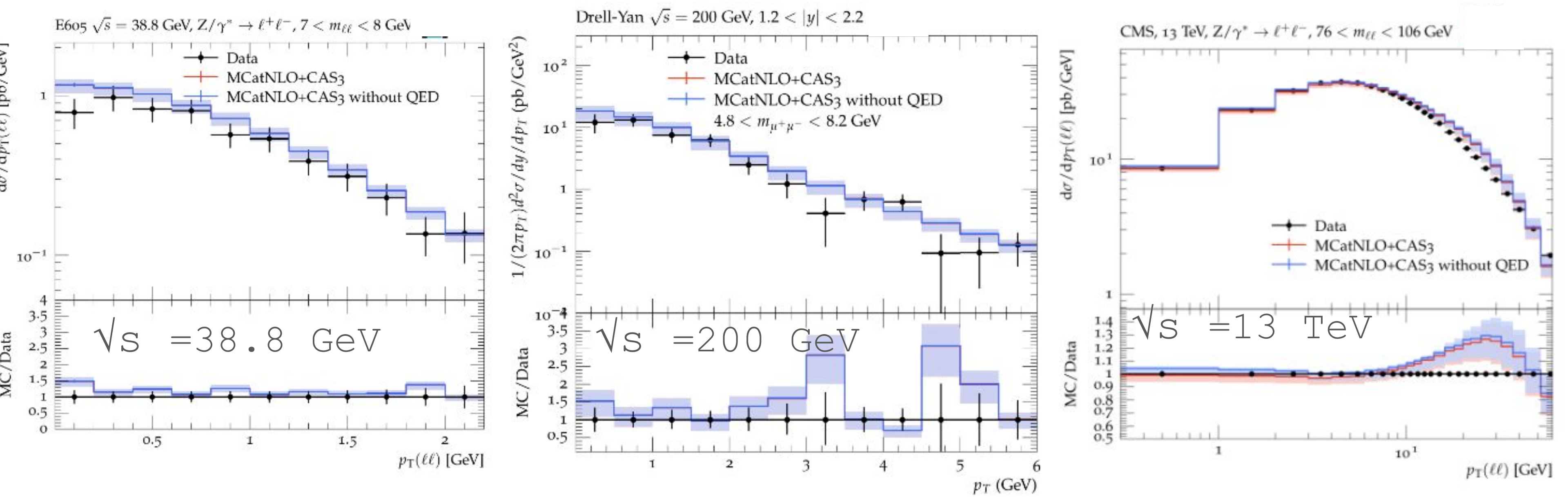


Low p_T values sensitive to these effects, probing the k_T value

Introduce a scale dependent $\alpha_s = \alpha_s(\mu'^2(1 - z)^2) = \alpha_s(q_T^2)$

PBTMD: Comparisons with various experiments results

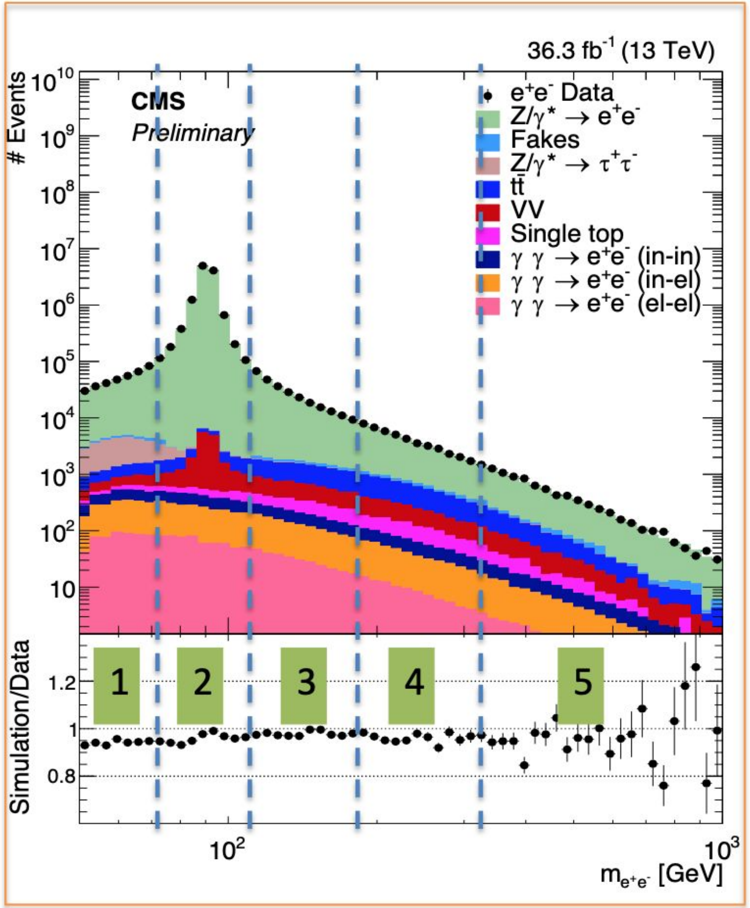
- Fitted only to HERA Data (named *PB-NLO-2018 set2*) (q_s=0.5 GeV)
- Compared to several measurements existing at range

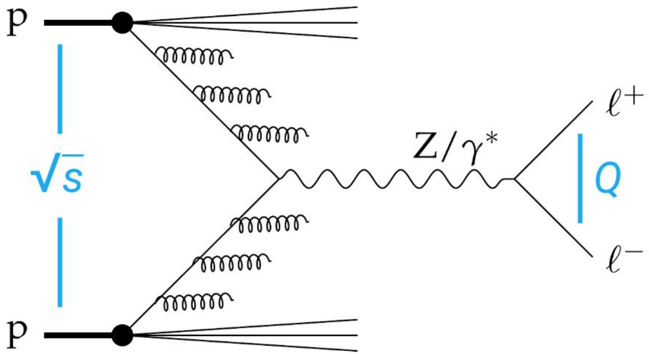


- Very good description for all √s w/o extra fitted parameters

Fit of α_s: Using DY measurement over wide mass range at 13 TeV

CMS: EPJ C 83 (2023) 628



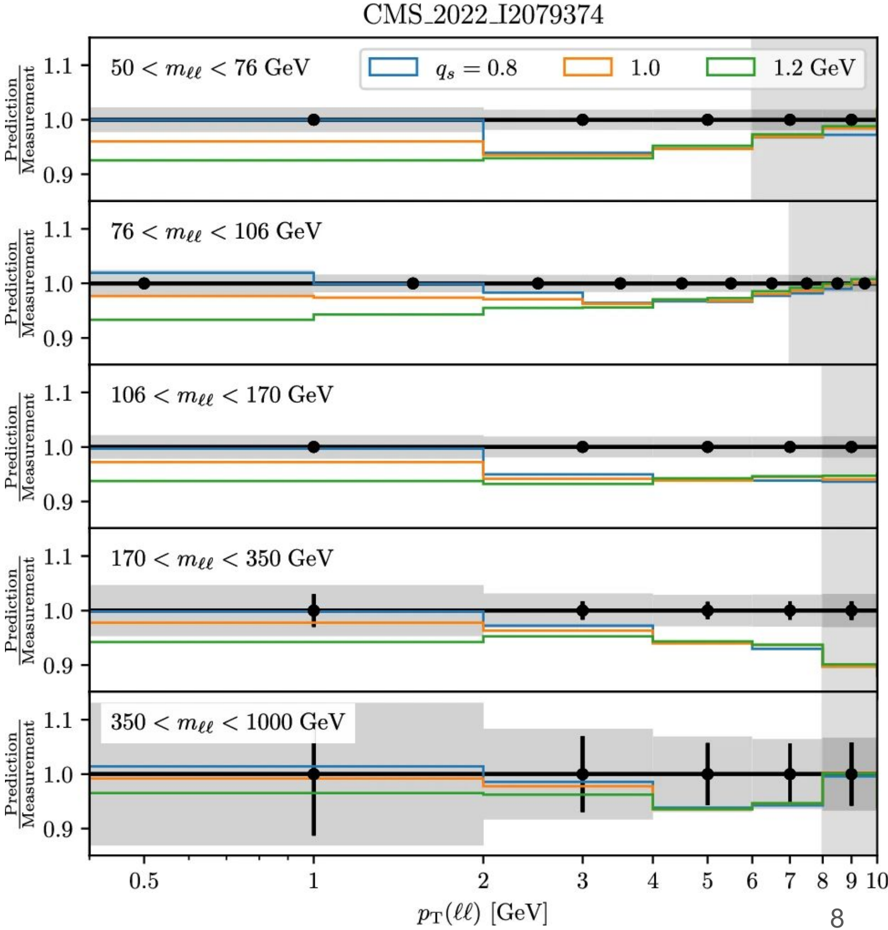


- Measurement of p_T^{ll} carried out in 5 mass bins
- Compared to traditional collinear MC as well as predictions with TMDs

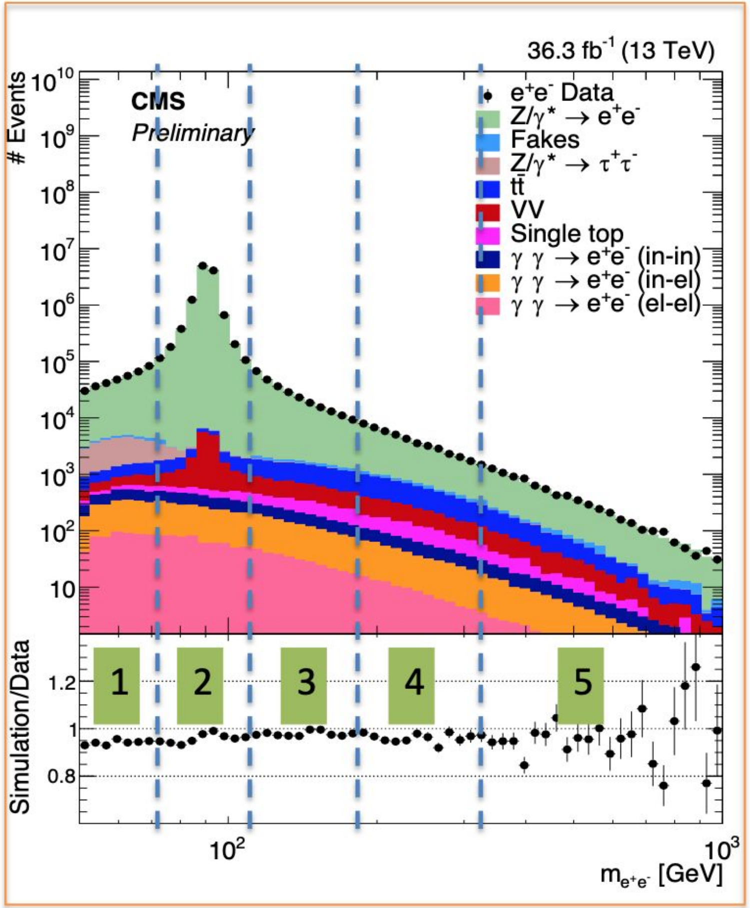
intrinsic k_T: Sensitivity to low p_T CMS data

- Low-pT DY data is sensitive to the quark kT distributions
- In PB TMD:
  - Gaussian distribution at $\mu_0 = 1\ \mathrm{GeV}$
  - Width given by $\sigma = q_s / \sqrt{2}$
  - Evolved to the scale of interest

Can be used to fit the q_s to CMS results, using full systematics



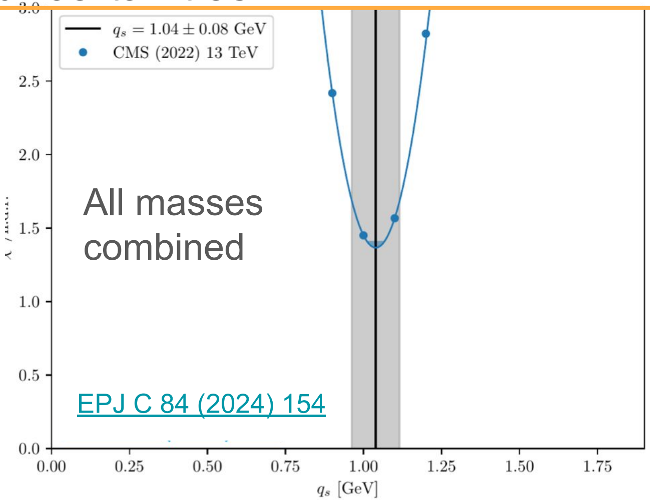
How to extract the qs variable



The qs variable in the PB-NLO-Set 2 is varied and compared to the CMS data in each mass bin.

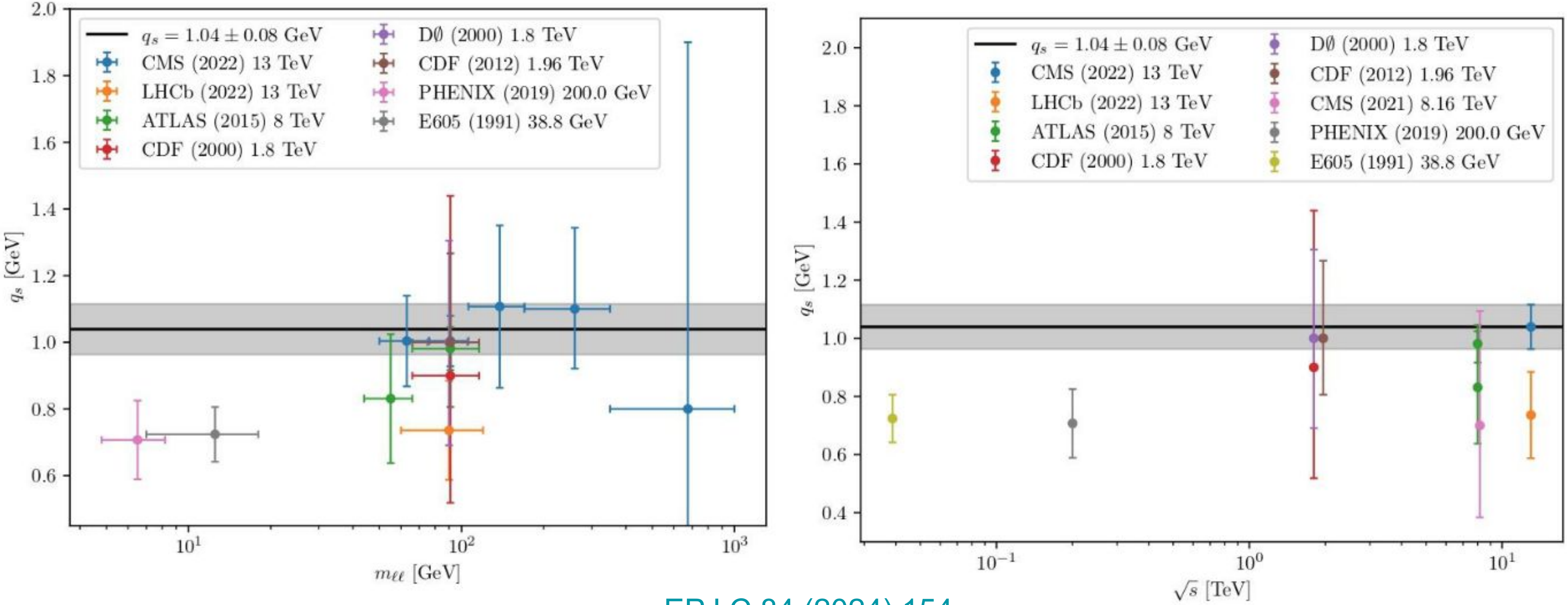
$$\chi^2 = \sum_{i,k} (m_i - \mu_i) C_{ik}^{-1} (m_k - \mu_k)$$

X^2 minimized to extract the qs, where the Cik are the covariance matrices for measurement and theory uncertainties



qs obtained as
1.04 GeV

intrinsic k_T: Comparison with other experiments



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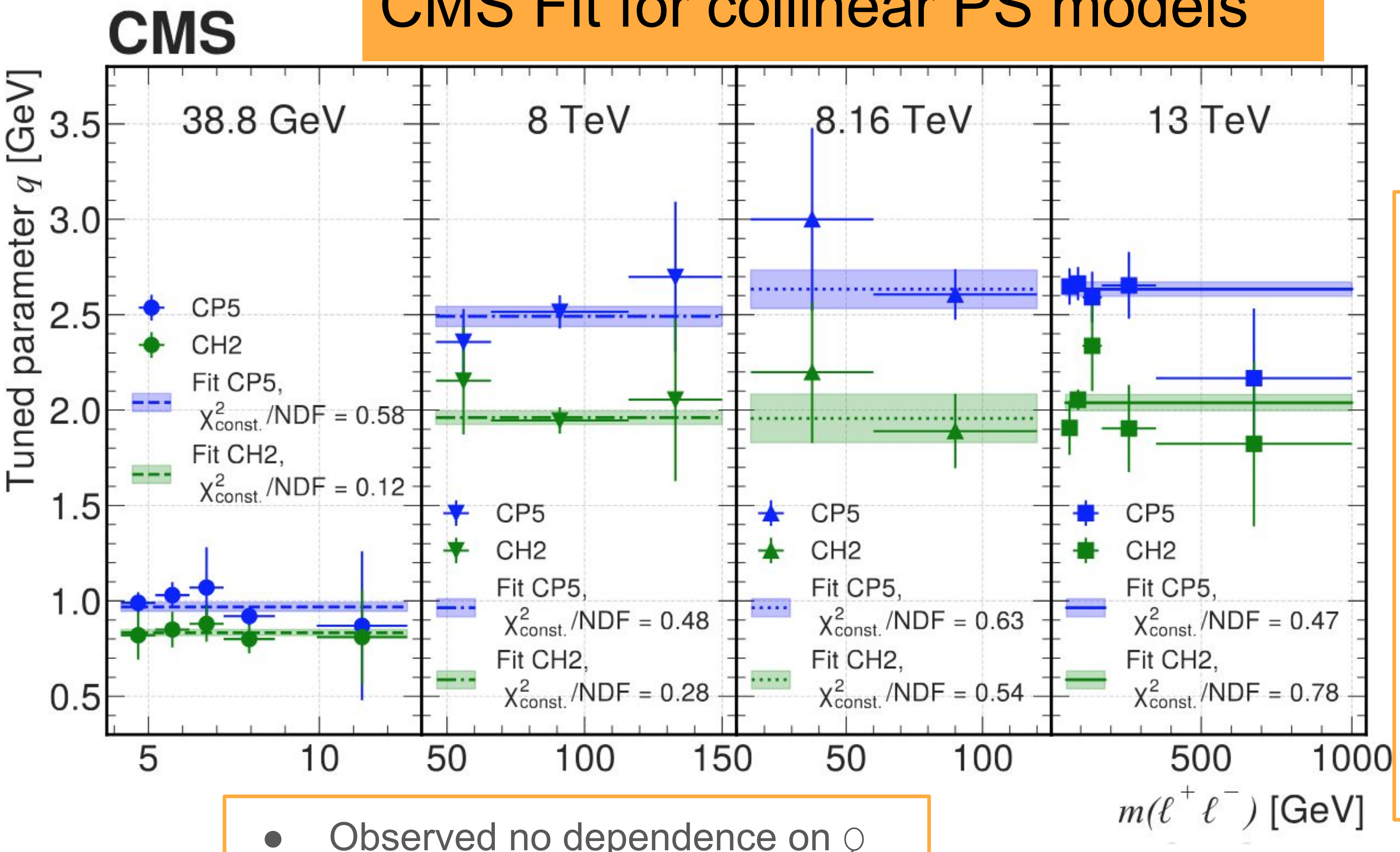
- Compared to q_s values obtained from other experiments.
    - ~Consistent values of q_s for a large range of DY invariant masses

CMS Fit for collinear PS models



CMS-GEN-22-001, submitted to PRL

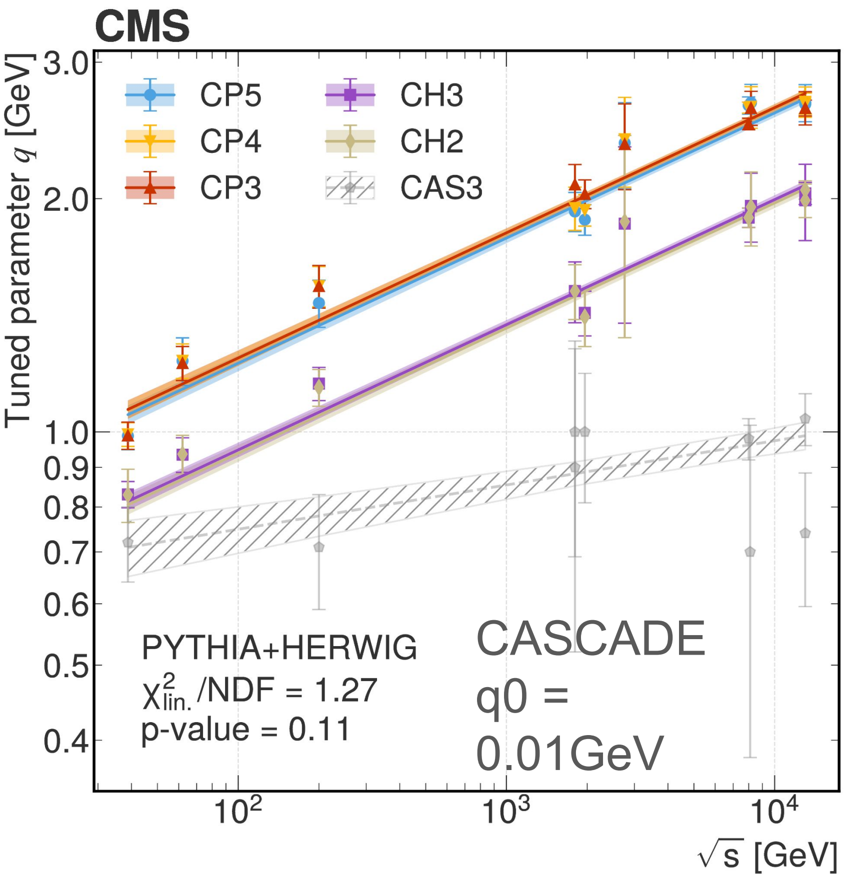
Parallel study by CMS using general purpose MC generators (Pythia and Herwig)

(PS with collinear PDF)

Harder values of q_s wrt PBTMD

- Observed no dependence on Q
- Strong dependence on $\sqrt{s}$

Dependency on srqt(s): Collinear vs PDTMD

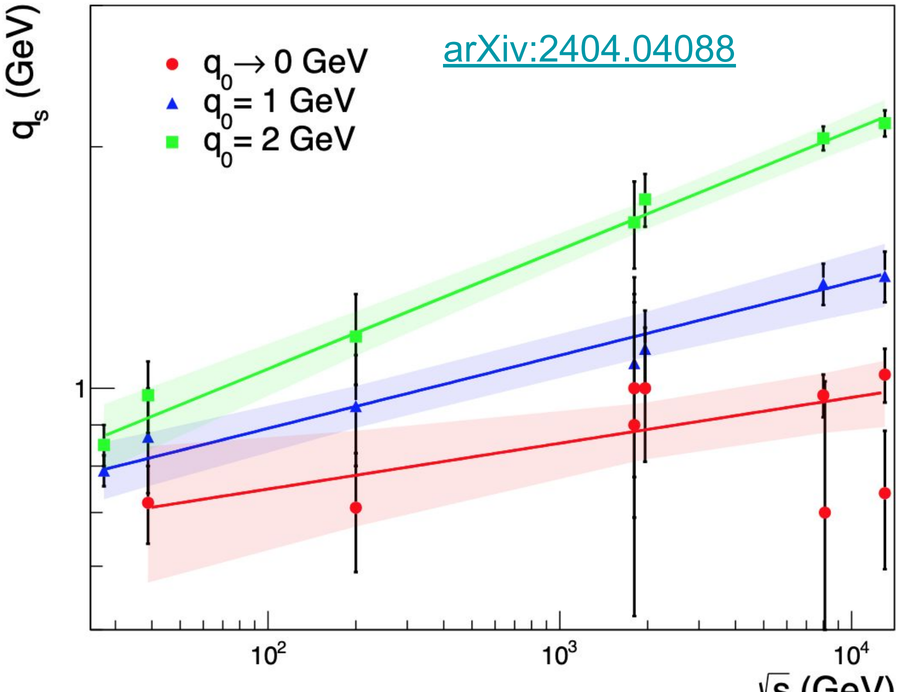


CMS-GEN-22-001, submitted to PRL

- Slope observed for the CMS study on Herwig (CH X) and Pythia (CP X) PS models
- Cascade PBTMD results show a milder slope, reducing further with q_0 (soft emissions for > q_0)
- A study has been carried for PBTMD, to mimic the coll PB results

introduce energy dependence of the intrinsic-kT in PB

Try to mimic parton-shower event generators by demanding a minimal parton transverse momentum ($q_0 = 1$ and 2 GeV) $\rightarrow q_T > q_0$
Real emissions with $z > (1-q_0)/\mu'$ neglected



For every q_0 value, all the measurements are fitted to extract a qs
An increasing trend wrt $\sqrt{s}$ is observed for higher values of q_0
This can be interpreted as if the lack of soft radiations has to be compensated by artificially large qs

Conclusions & Outlook

- Challenge to get a global description of dynamically generated transverse momentum throughout a phase-space spanned
  - Traditional general purpose MC generators are not able to describe coherently the evolution wrt Q and $\sqrt{s}$
  - PBTMD provides promising results, with milder dependence on $\sqrt{s}$
  - Simple, coherent estimation of the transverse momenta with few parameters
    - Providing universal description
    - Intrinsic k_T has been extracted from data
    - First principle, it is possible in general purpose MC generators.

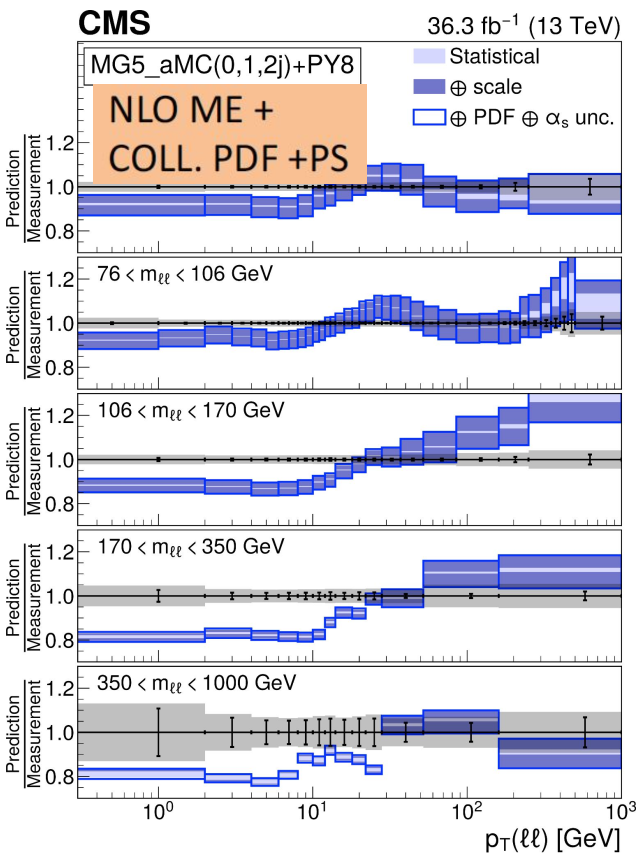
THANK YOU

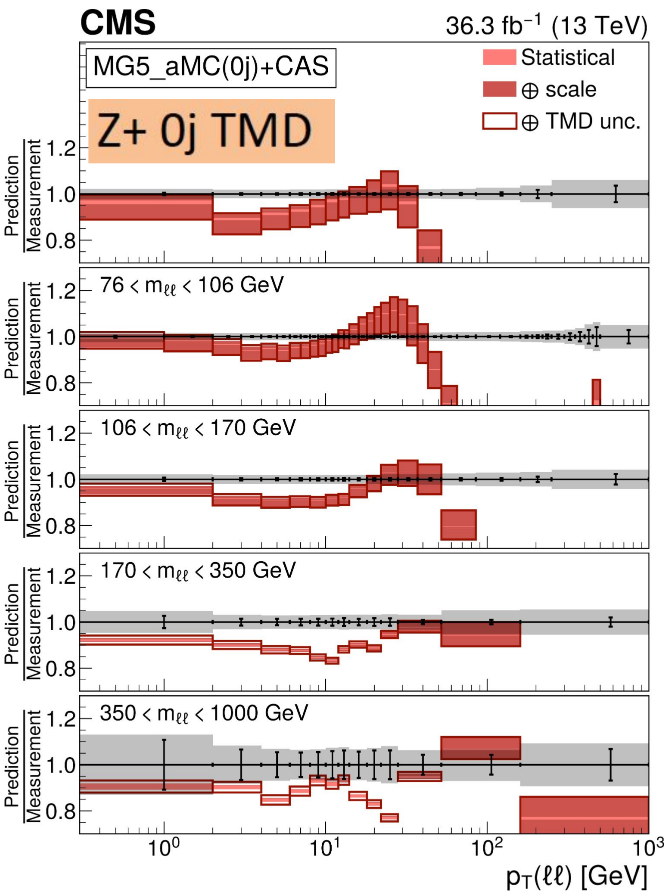
BACKUP

CASCADE

- Implementing PB-TMD in the ISR
  - Generates the full hadron event record according to the HEP common standards
- FSR handled by pythia
- Can be linked to other generators for the Martix Element part
- Used extensively for comparing experimental results
- Supports multileg merging à la TMD merging

DY over wide Q range





- Need higher order pQCD for high pT region
- Special treatment needed for low pT region.
- PBTMD shows an overall good agreement in the low pT region

Other measurements used

Experiment	Collision type	$\sqrt{s}$ [GeV]	Q [GeV]
E866/NuSea [11,12]	pp/pd, fixed target	38.8	4–12.85
R209 [13]	pp	62	5–8
PHENIX [14]	pp	200	4.8–8.2
D0/CDF [15,16]	$p\overline{p}$	1800	$m(Z)$
D0/CDF [17,18]	$p\overline{p}$	1960	$m(Z)$
CMS [19]	pp	2760	$m(Z)$
ATLAS [20]	pp	8000	46–150
CMS [21]	pPb	8160	15–120
CMS [22]	pp	13000	50–1000
LHCb [23]	pp	13000	$m(Z)$

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