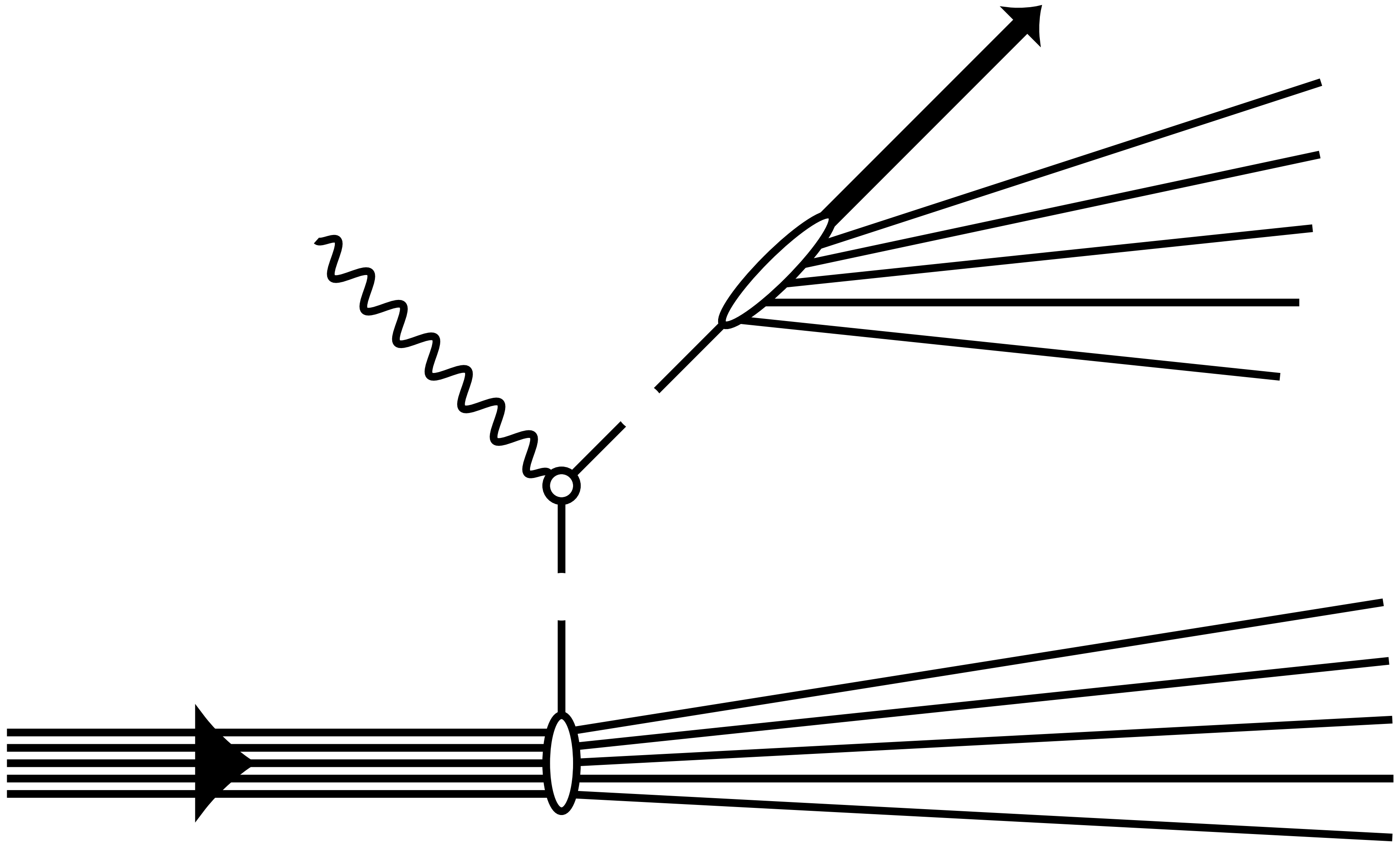
Towards a study of the effects of dynamical factorization breaking at LHCb

Jordan Roth / University of Michigan : April 2021

Workshop on Deep-Inelastic Scattering (and Related Subjects)

On behalf of the LHCb Collaboration

Factorization connects partonic physics to hadronic physics



$$d\boldsymbol{\sigma} = f \otimes d\hat{\boldsymbol{\sigma}} \otimes D + \mathcal{O}(\Lambda/Q)$$

Factorization allows to...

- compute hadronic cross sections
- use parton shower event generators
- resum multi-scale observables
- label stages of hadron production
- use probability interpretation
- et cetera...

The connection is **rigorous,** as compared to Monte Carlo hadronization models.

The connection fails in some limits. Don't know by how much, or every limit.

No Generalized TMD-Factorization in the Hadro-Production of High Transverse Momentum Hadrons

... by Ted Rogers and Piet Mulders.

Phys. Rev. D **81** (2010) 094006 / arXiv:1001.2977

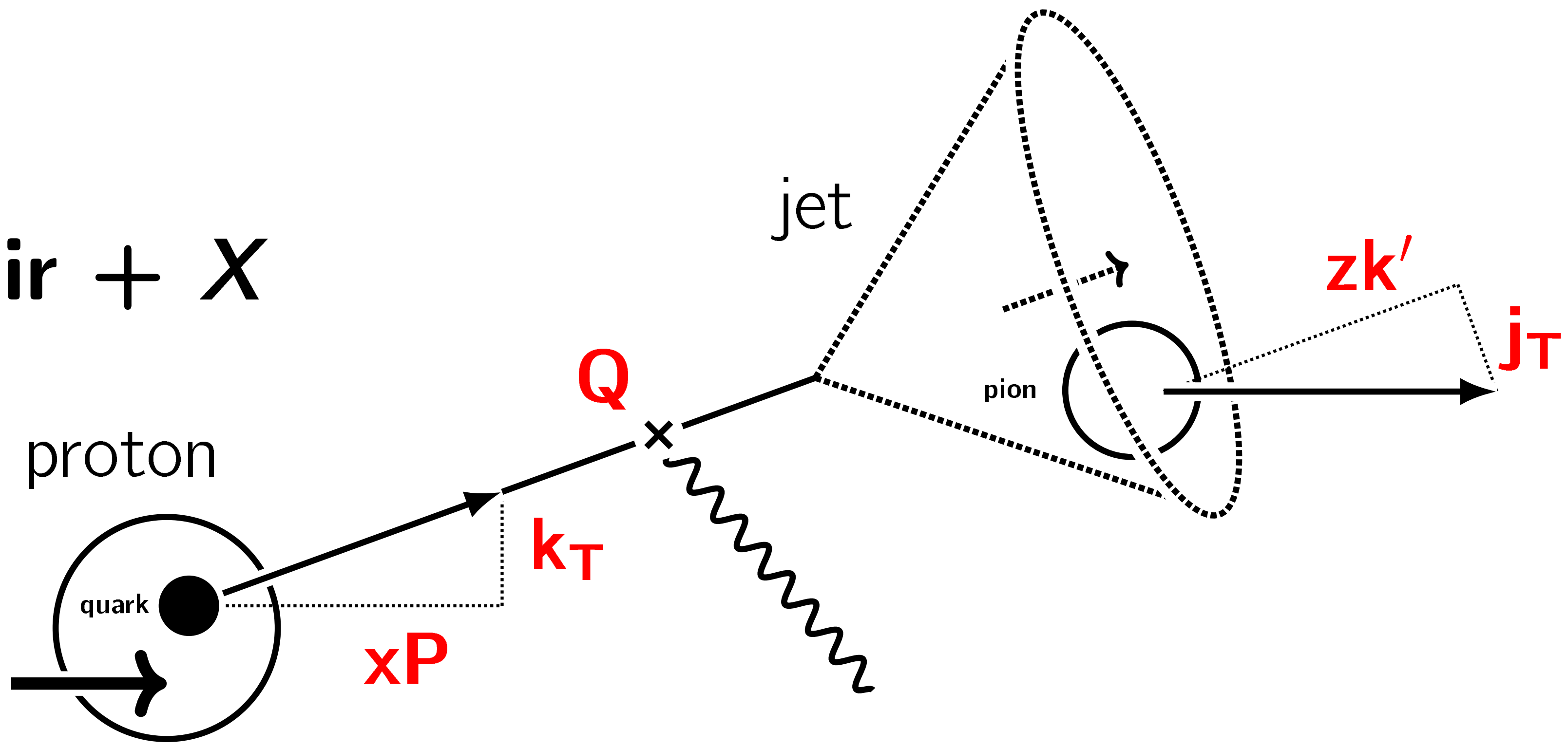
It gives us a specific channel to look into:

$$p + p \to \textbf{nearly-back-to-back hadron pair} + X$$

Or $pp \to$ dijets $+ X$, or $pp \to Z$+jet $+ X$, aut cetera...

The breakage is not suppressed at high energy.

So, the effect should be cleanly isolated.



"TMD" means "transverse momentum-dependent" factorization.

Note: TMD factorization is the same as k_T factorization, or Collins-Soper-Sterman factorization.

The Rogers-Mulders result does not generalize easily

Momentum imbalance (q_T) spectra **should** factorize for...

double-inclusive e^+e^- annihilation	$e^+e^- \to hhX$
semi-inclusive deep inelastic scattering	$ep \to ehX$
Drell-Yan dilepton production	$pp \to \ell^+\ell^-X$

Note the...
number of collinear regions.
exclusivity of the measurement.

In fact: any IR-safe single-differential observable *might* factorize in these channels.

Matt Schwartz, Kai Yan, and Huaxing Zhu: Phys. Rev. D **97** (2018) 096017 / arXiv:1801.01138

And, wide-angle dihadron hadroproduction could factorize in collinear framework.

John Collins, Jianwei Qiu: Phys. Rev. D **75** (2007) 114014 / arXiv:0705.2141

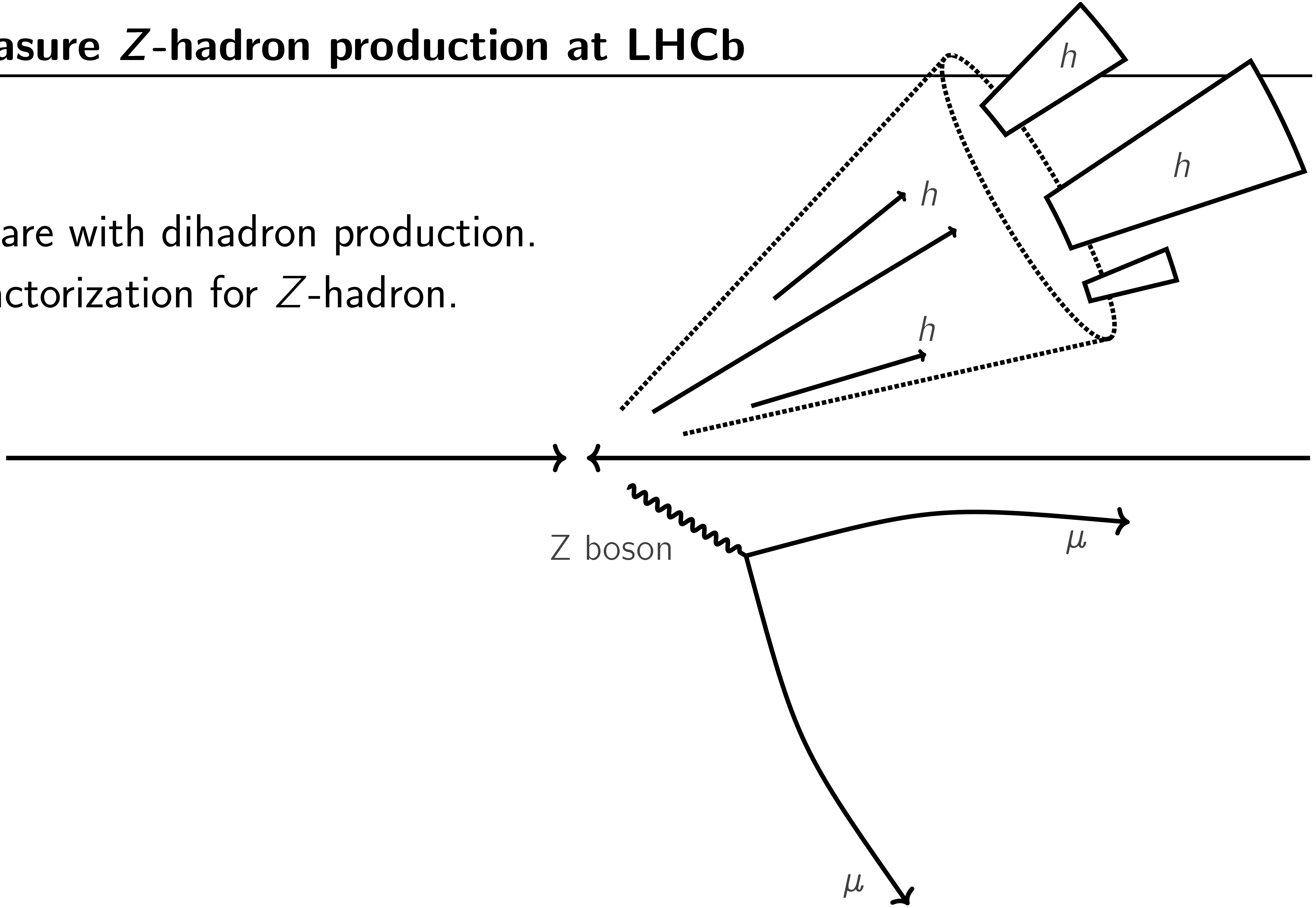
There is no list of which observables factorize under which framework.

For proofs of the three processes that can be factorized, read John Collins' "Foundations of perturbative QCD."

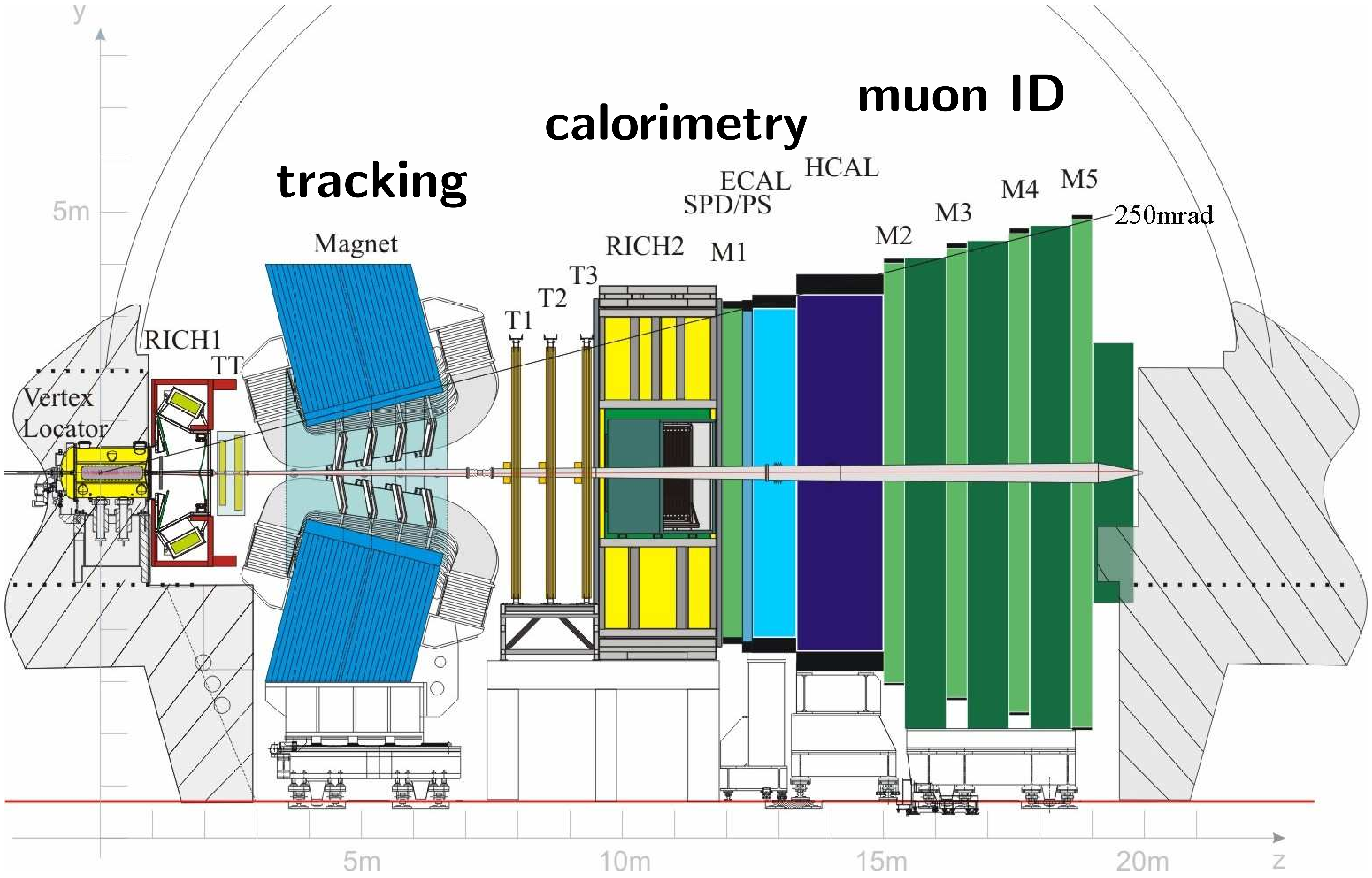
We want to measure Z-hadron production at LHCb

Allows us to compare with dihadron production.

Also: test TMD factorization for Z-hadron.



We want to measure Z-hadron production at LHCb



low pile-up

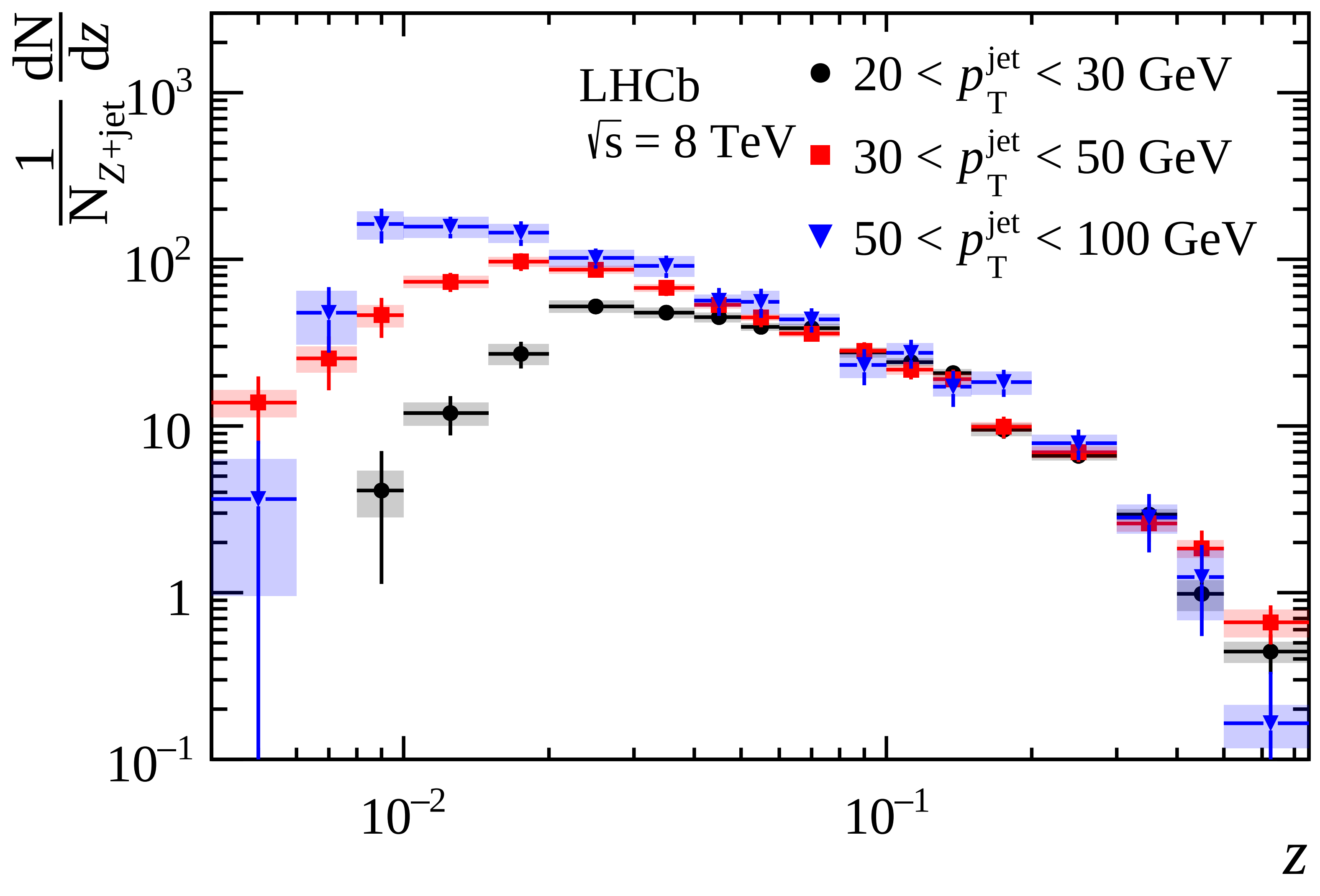
high Z boson yield

Hope that you caught the talk by Charlotte Van Hulse on Monday, and Sookhyun Lee's talk on Wednesday about hadronization studies at LHCb!

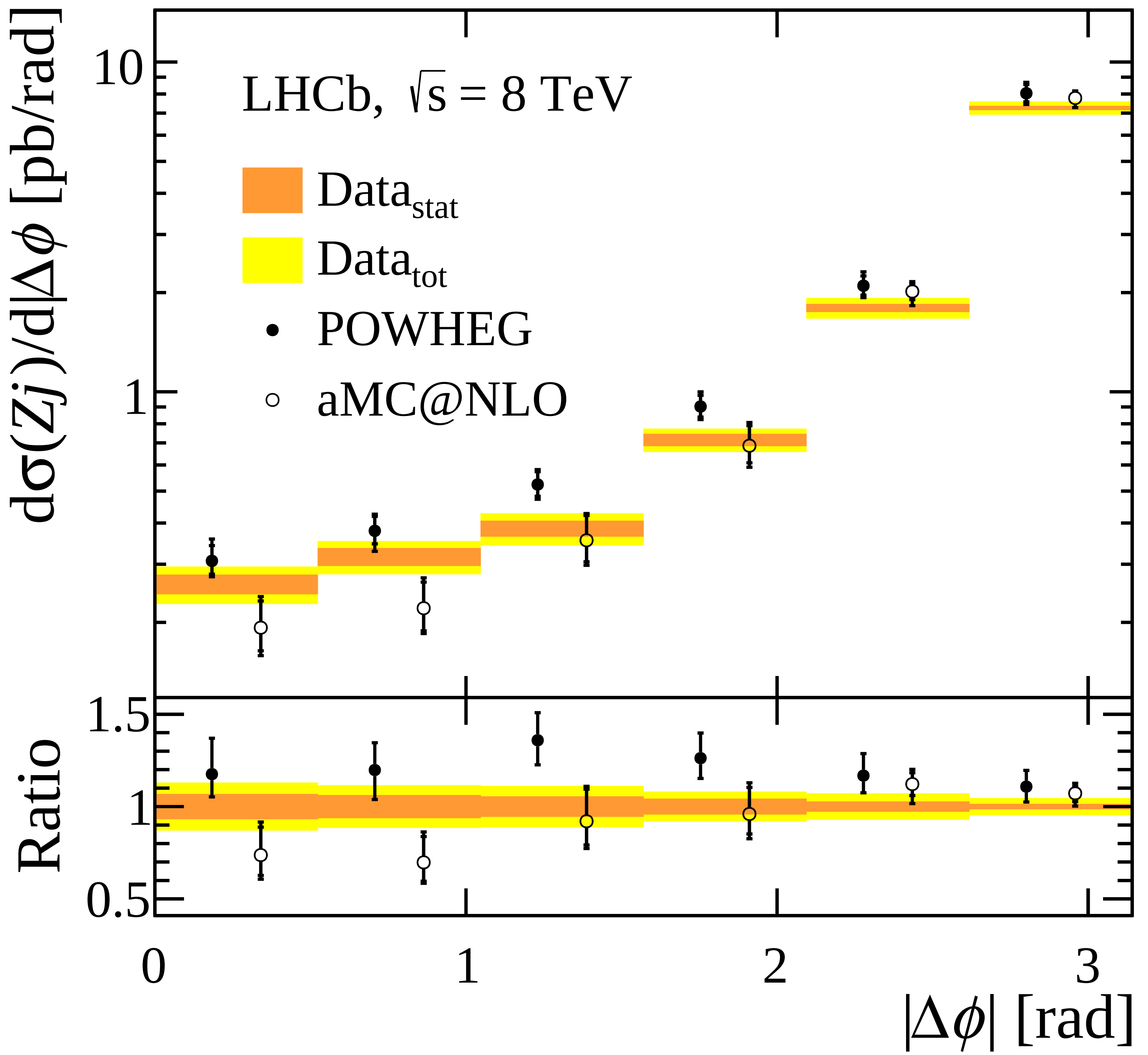
Figure from JINST **3** (2008) S08005.

We want to measure Z-hadron production at LHCb

Phys. Rev. Lett. **123** (2019) 232001 / arXiv:1904.08878



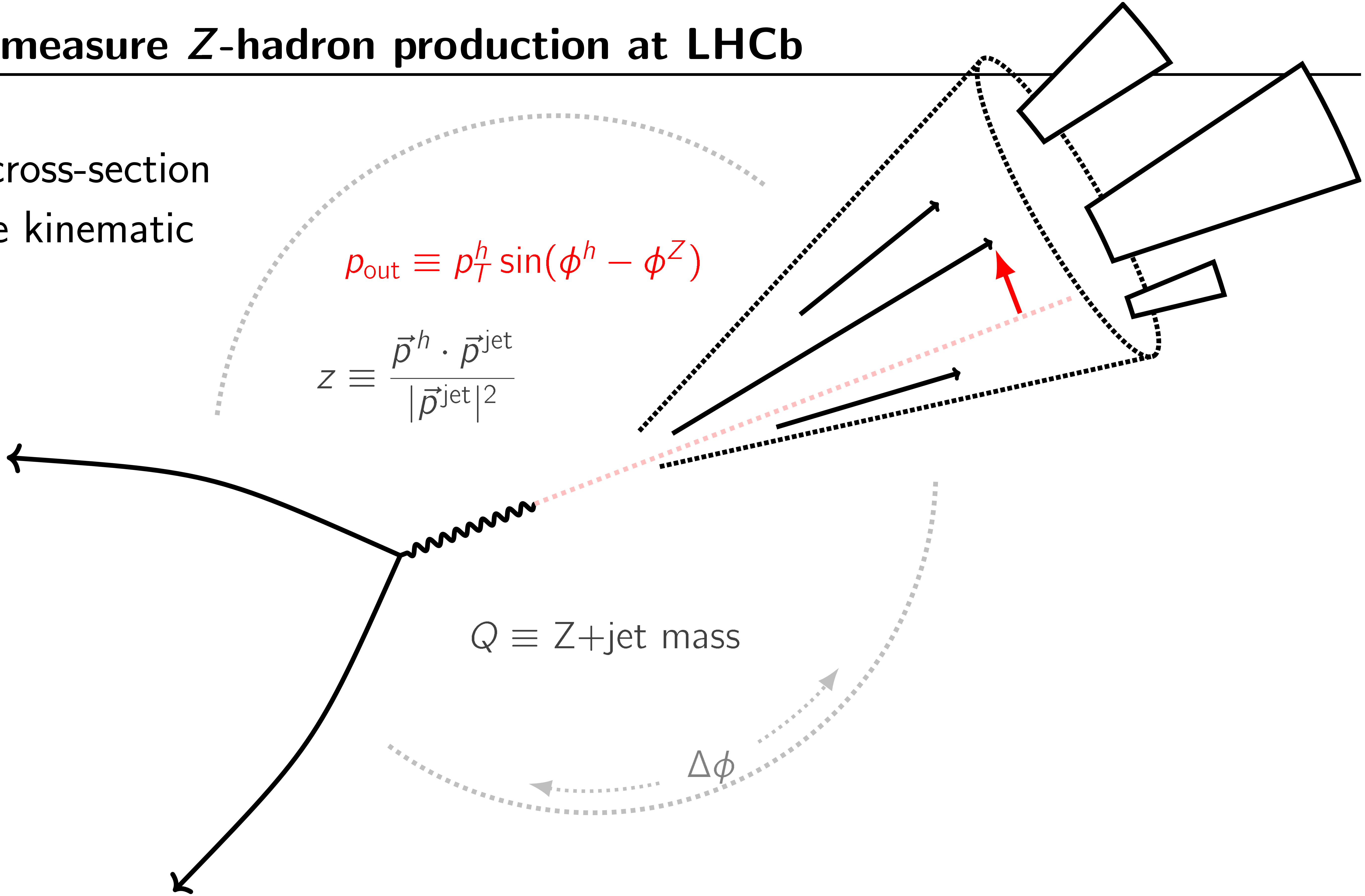
JHEP **05** (2016) 131 / arXiv:1605.00951



LHCb has already published several measurements in the Z+jet channel.

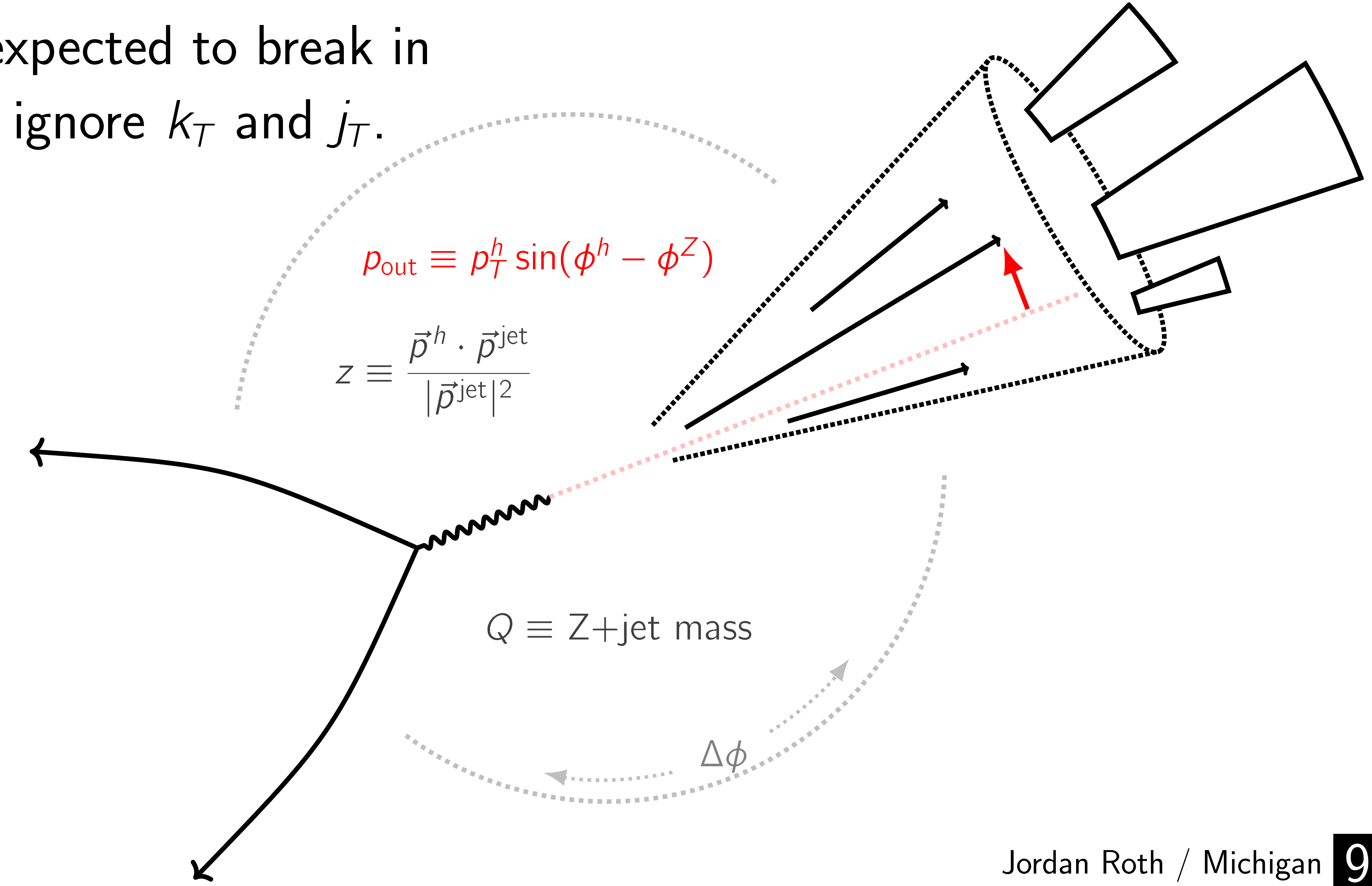
We want to measure Z-hadron production at LHCb

Use hadronic cross-section binned in three kinematic variables...



We want to measure Z-hadron production at LHCb

p_{out} : probe transverse momenta generated by showers and long-range dynamics in initial state and final state.
Because: factorization is not expected to break in collinear framework, where we ignore k_T and j_T.



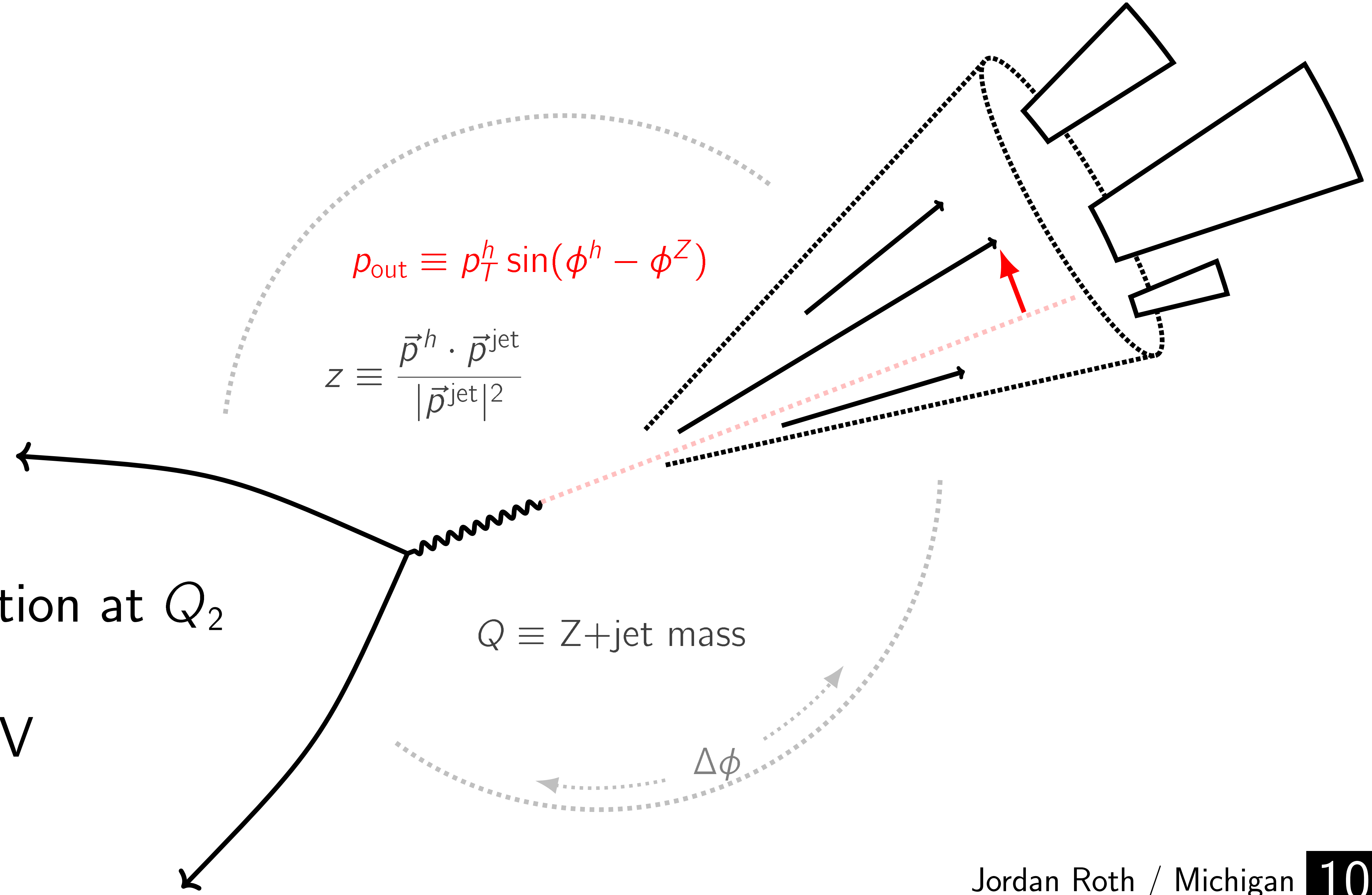
We want to measure Z-hadron production at LHCb

Q : probe evolution of p_{out} distributions. Collins-Soper-Sterman evolution depends on factorization and does not require high-quality global fits.

The rough idea is...

1. Measure p_{out} distribution at Q_1
2. Evolve distribution to Q_2
3. Measure distribution at Q_2
4. Compare measurement/calculation at Q_2

Note: we have $Q \sim 100 - 250$ GeV



We want to measure Z-hadron production at LHCb

$\underline{z\ :}$ control for fragmentation. Exclude extreme low and high z where calculation is difficult; probe $p_{\text{out}} \sim j_T + z\, k_T$ mixture.

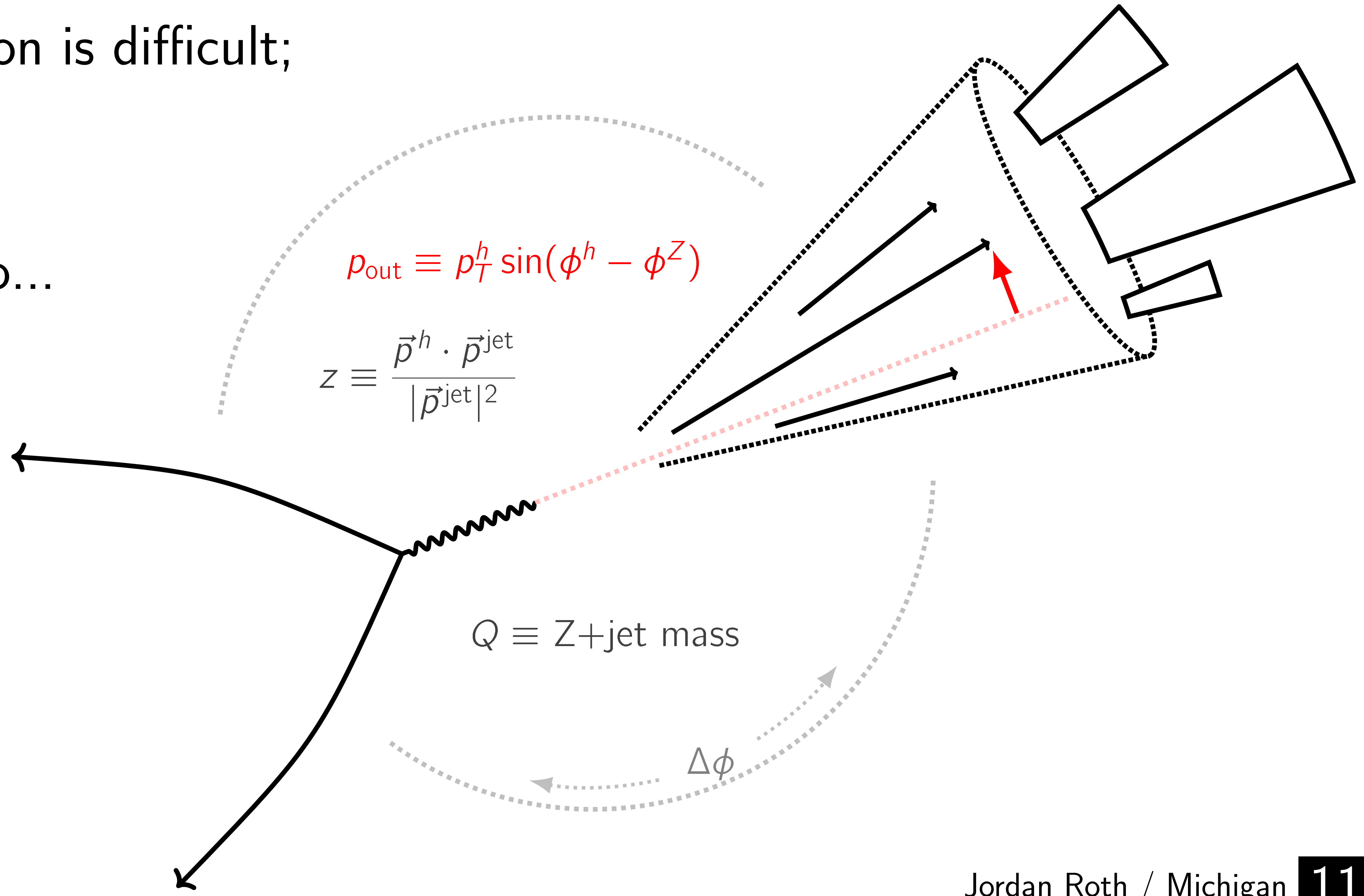
Note: we have z bins similar to...

$\sim 0.01 - 0.03$

$\sim 0.03 - 0.06$

$\sim 0.06 - 0.1$

$\sim 0.1 - 0.7$

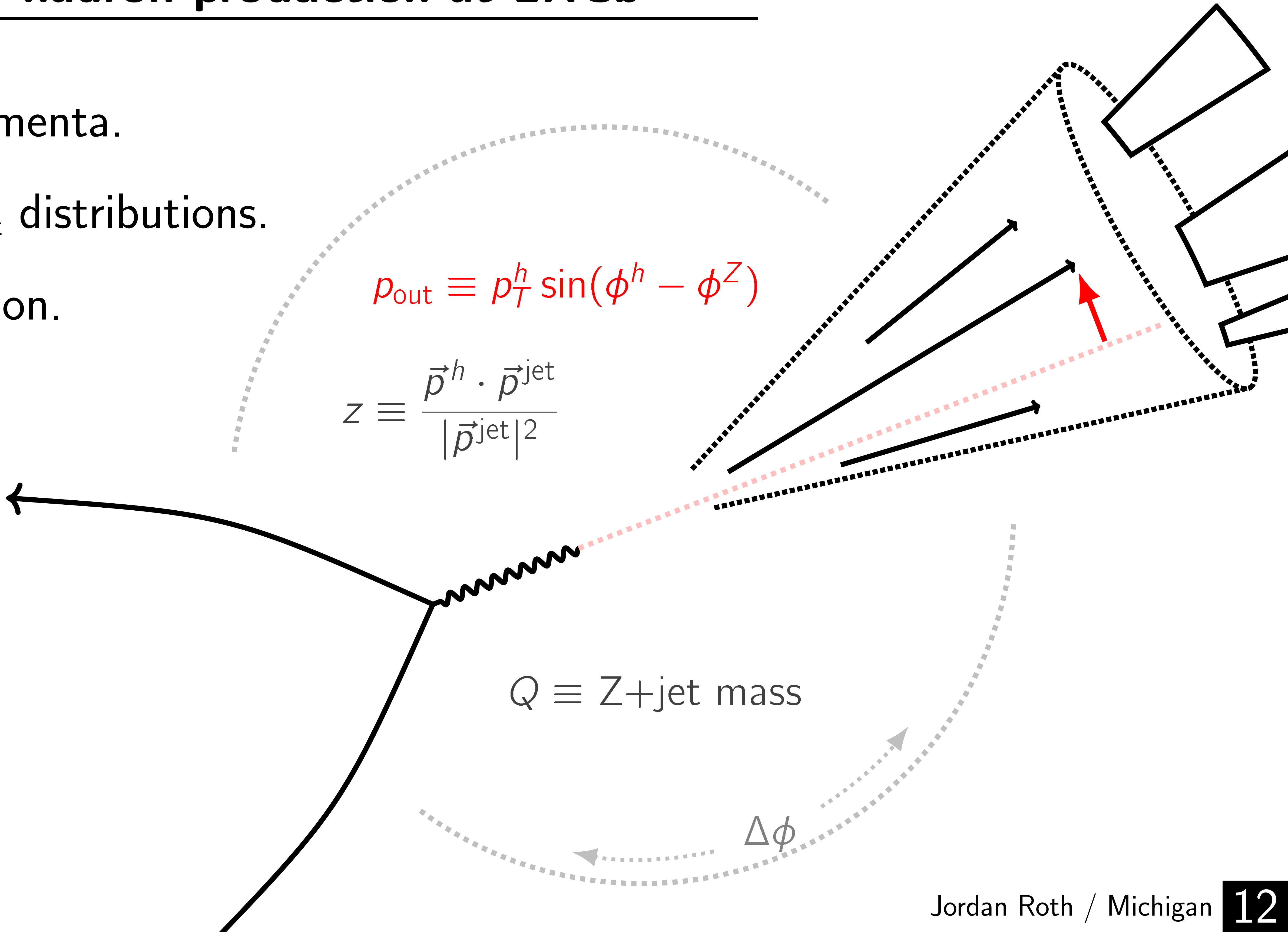


We want to measure Z-hadron production at LHCb

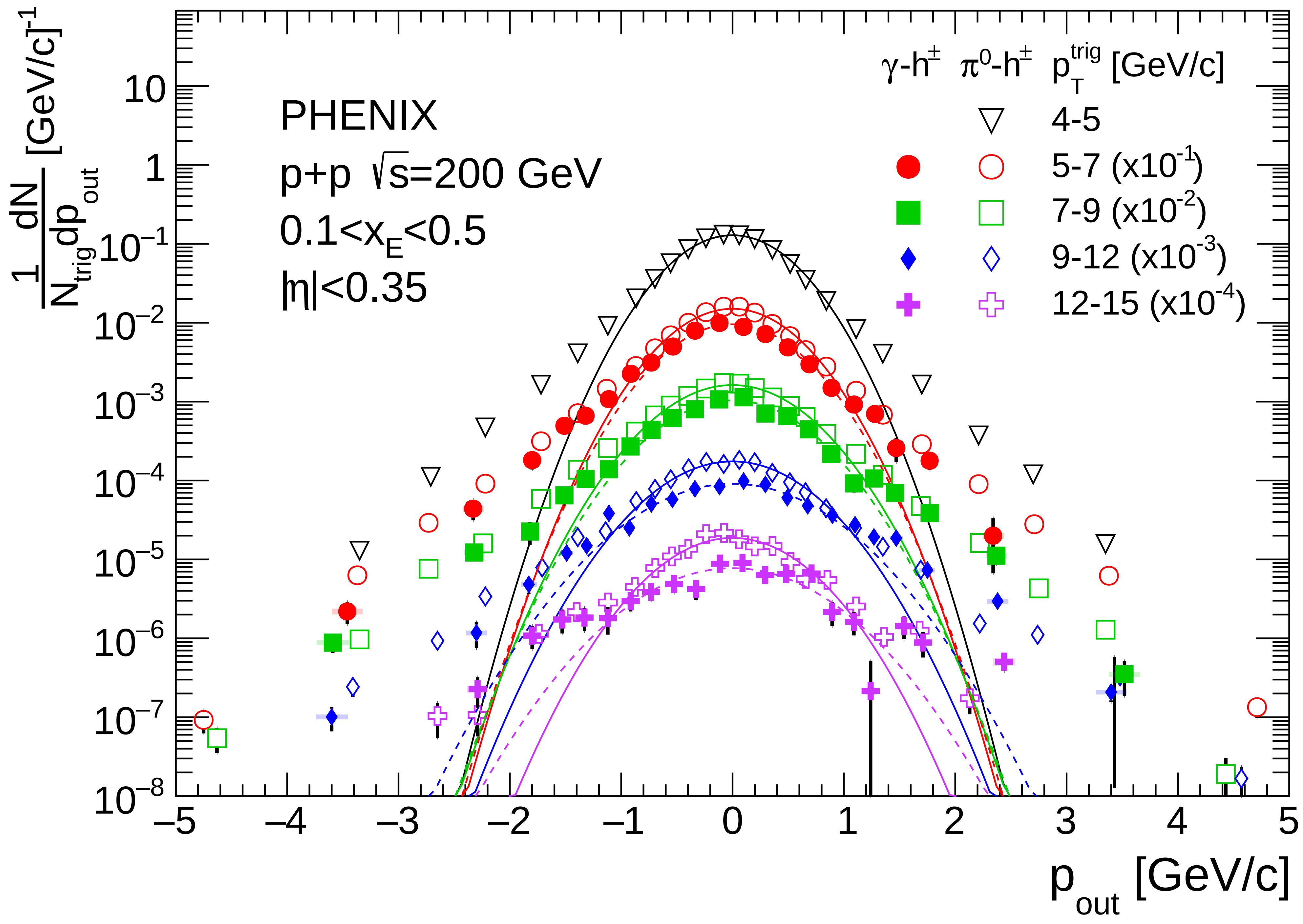
p_{out} : probe transverse momenta.

Q : probe evolution of p_{out} distributions.

z : control for fragmentation.



PHENIX has measurements with γ-hadrons and dihadrons (no jets)



$p_T^{\rm trig} \sim Q$

$x_E \sim z$

$p_{\rm out} \sim q_T$

The curves are Gaussian fits to the data in the core region.

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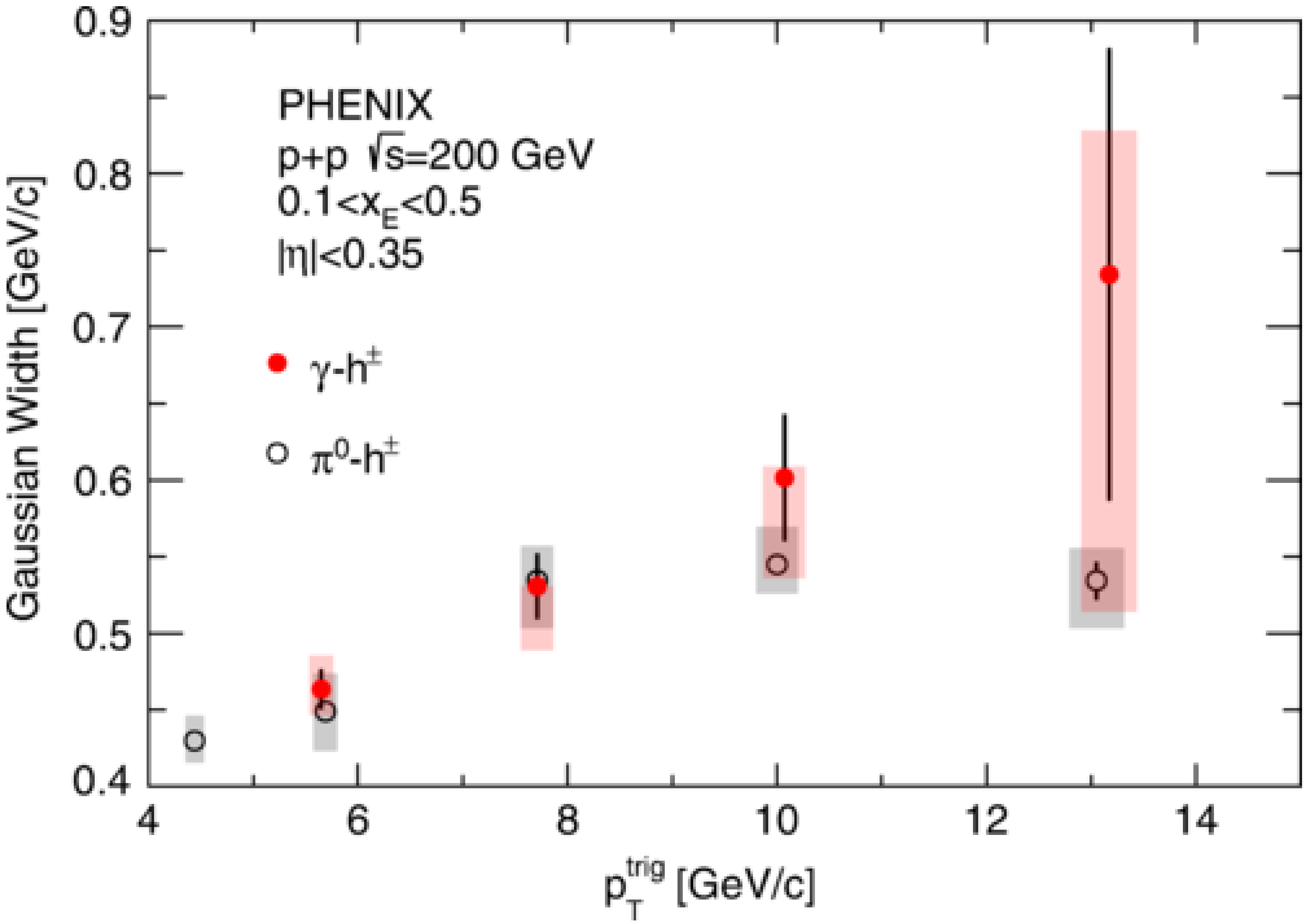

$p_T^{\text{trig}} \sim Q$

$x_E \sim z$

$p_{\text{out}} \sim q_T$

Qualitatively: p_{out} widths increased with hard scale. No calculation yet.

Summary

We want to quantify the breakdown of transverse momentum-dependent factorization: a fundamental but as yet unverified prediction of QCD.

Factorization has a rigorous connection to QCD...

There is no list of which observables factorize...

Data that might be sensitive to the breakage already exist: from PHENIX. They probe the breakage via CSS evolution. More measurements from LHCb will probe a different energy and rapidity range: and, can use jets to get at z and Q.

Comments? Questions?