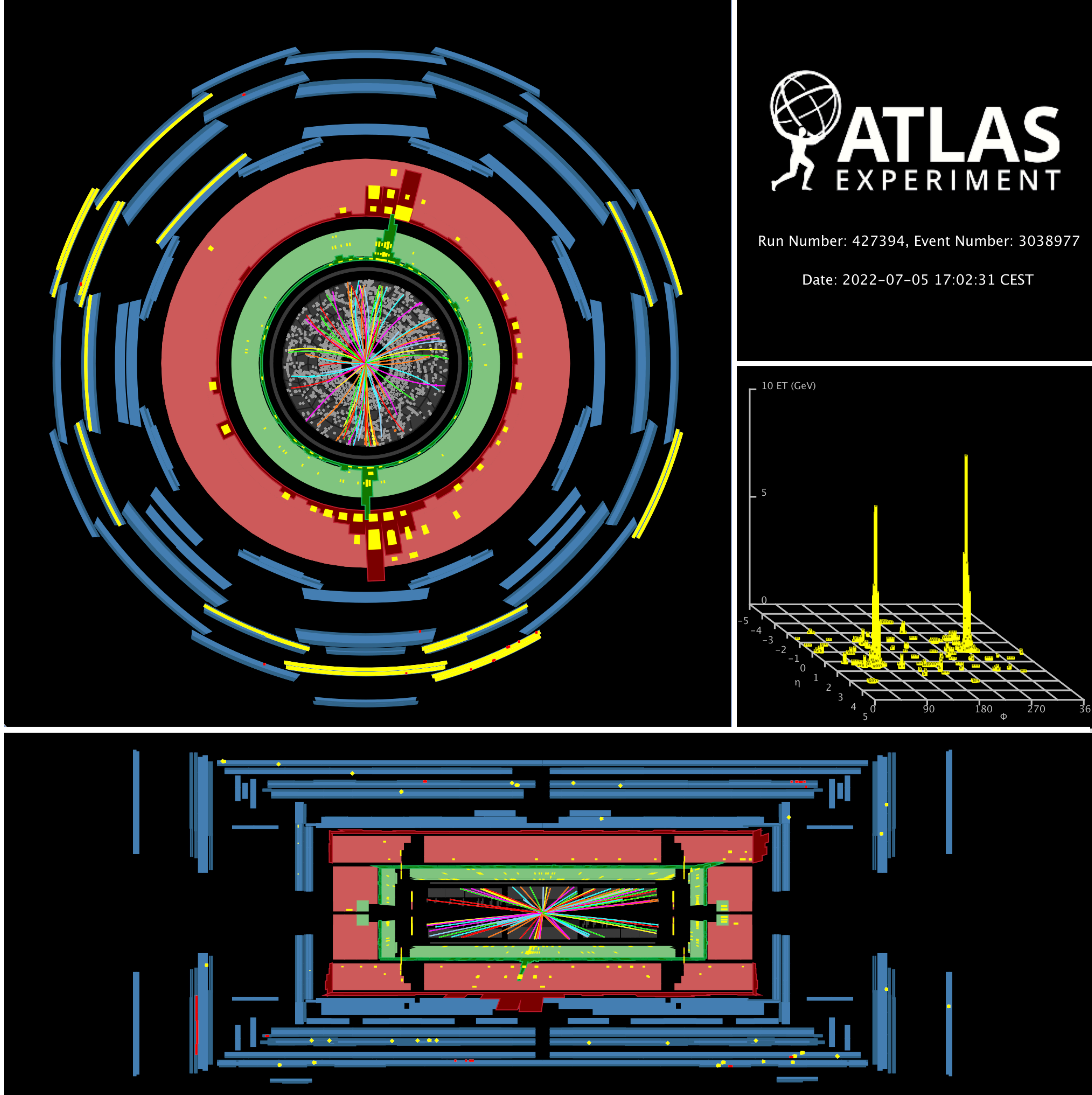
Predicting **QCD dynamics** at the HL-LHC

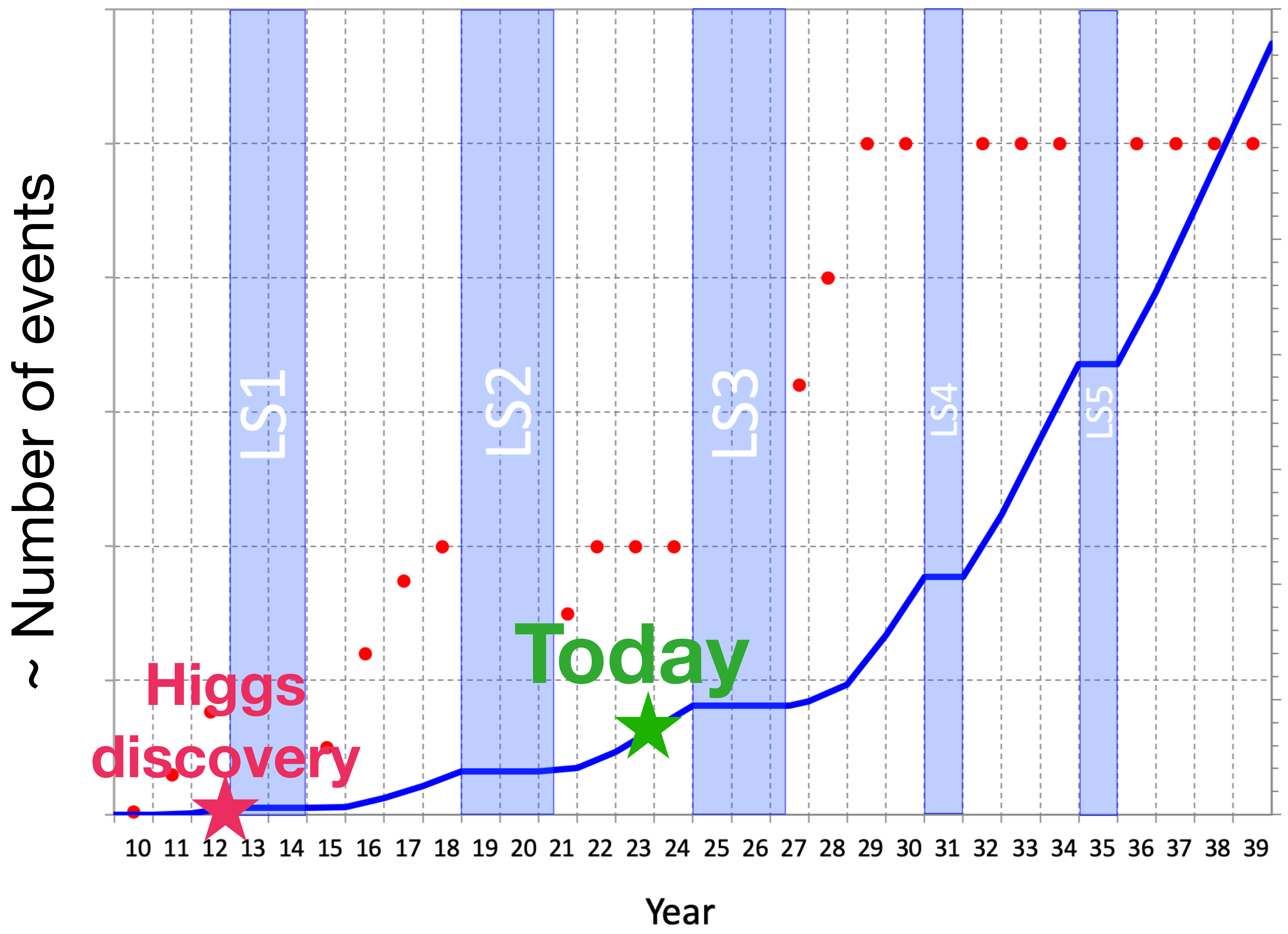
Alba Soto Ontoso

Physics Colloquium

BNL, 31st January, 2023



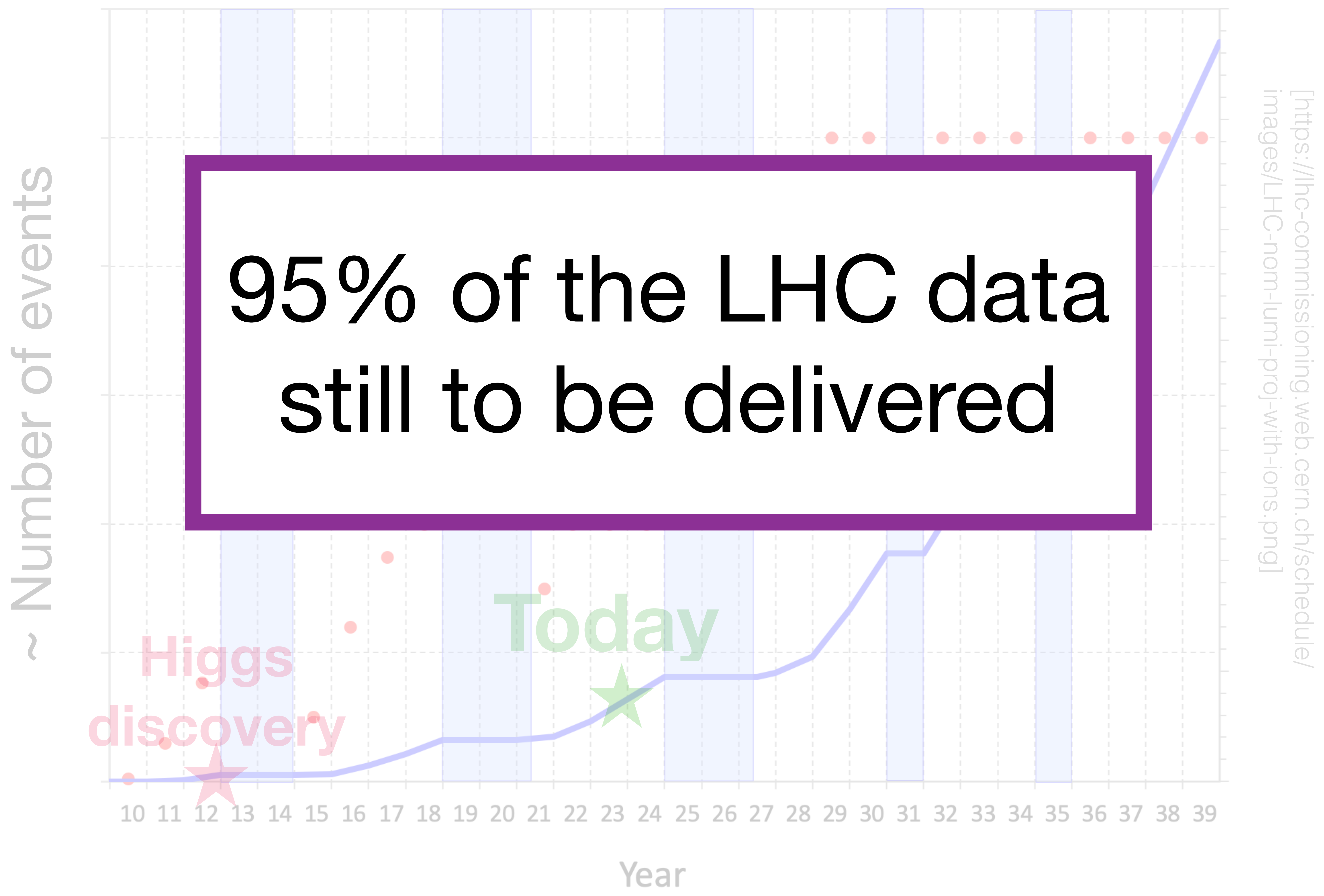
Time evolution of LHC performance



[https://lhc-commissioning.web.cern.ch/schedule/images/LHC-nom-lumi-proj-with-ions.png]

Time evolution of LHC performance

95% of the LHC data
still to be delivered



Global picture of HL-LHC physics program [CERN-2019-007, ATLAS-PHYS-PUB-2022-018]

Higgs sector

- Self-coupling
- Lifetime
- Higgs portal to Dark Matter
- Couplings to 2nd generation
- CP violating decays
- ...

Quark-Gluon plasma

- Temperature
- Viscosity
- Chiral magnetic effect
- p-O and O-O collisions
- Heavy-quark transport coefficients
- Quasi-particle structure
- ...

Standard model

- W boson mass
- Utimate PDFs from HL-LHC data
- Weak mixing angle
- Four top production
- ...

Beyond SM searches

- Supersymmetry
- Long lived particles
- Dark matter & dark sectors
- Leptoquarks
- ALPs
- ∞

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Higgs sector
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- Higg… Matte…
- Coup… gene…
- CP v…
- …

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- …ct
- …ns
- …rt coefficients
- …ure

A precise understanding of QCD is crucial for all milestones of the HL-LHC program

Standard model
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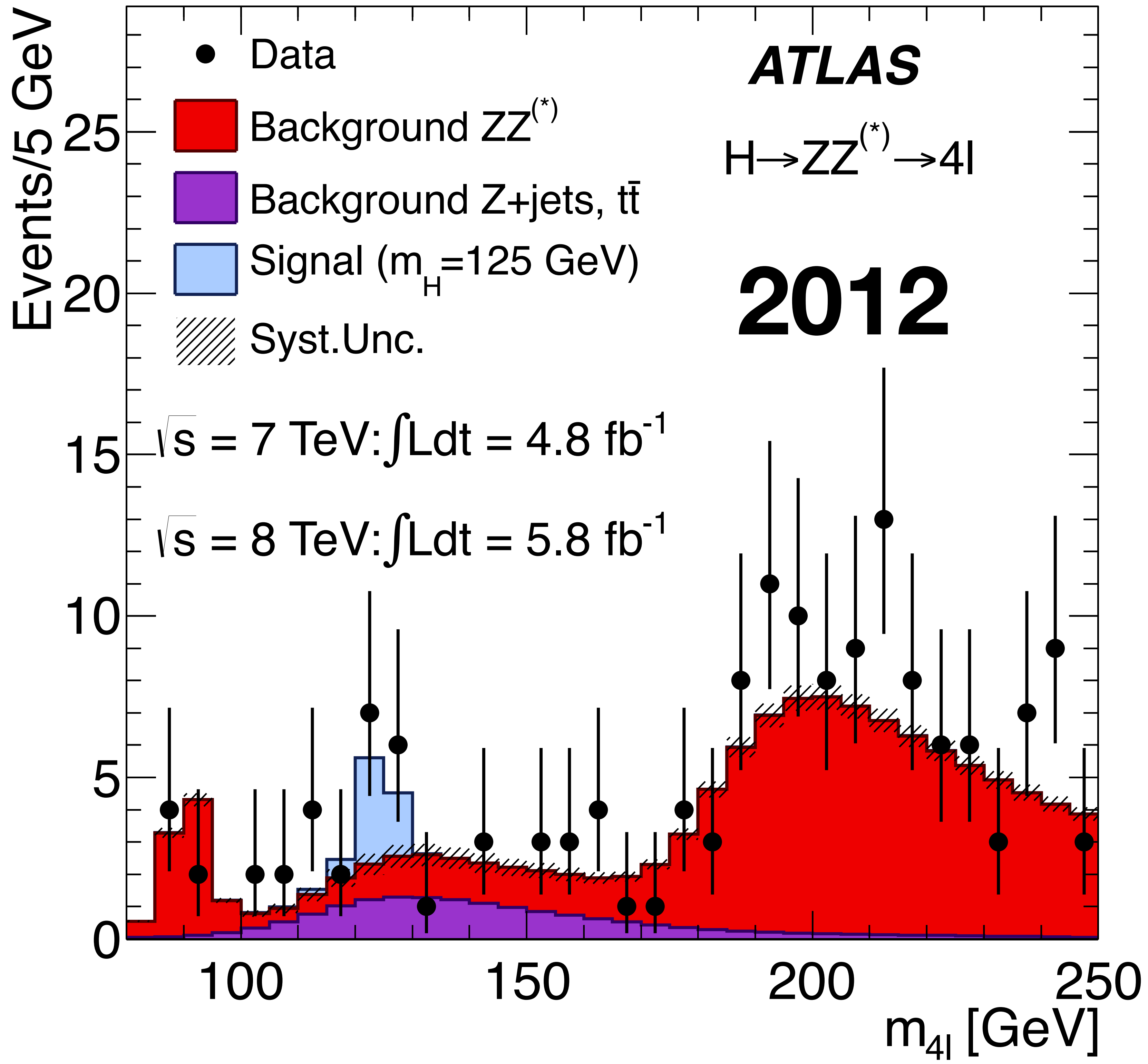
The holy grail of HL-LHC: trilinear Higgs coupling

In the Standard Model, the Higgs potential reads

$$V(\phi) = \lambda v^2 \phi^2 + \lambda \phi^4 = V(v) + m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

$$\phi = v + H$$

[ATLAS Phys.Lett.B 716 (2012) 1-29]



$$m_H = 126 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})\ \text{GeV}$$

The holy grail of HL-LHC: trilinear Higgs coupling

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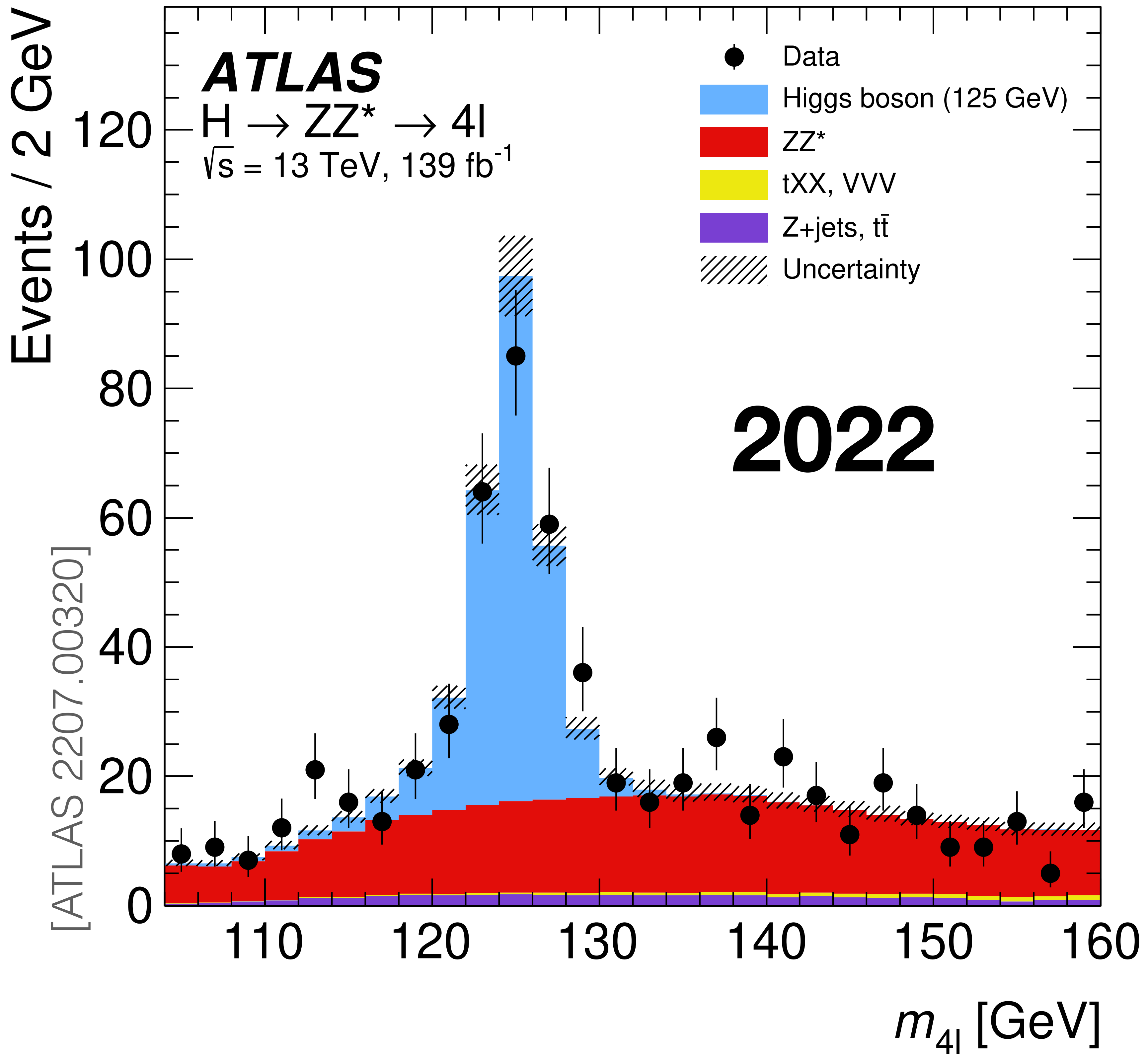

$$m_H = 124.99 \pm 0.17(\text{stat}) \pm 0.03(\text{syst})\ \text{GeV}$$

The holy grail of HL-LHC: trilinear Higgs coupling

In the Standard Model, the Higgs potential reads

$$V(\phi) = \lambda v^2 \phi^2 + \lambda \phi^4 = V(v) + m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

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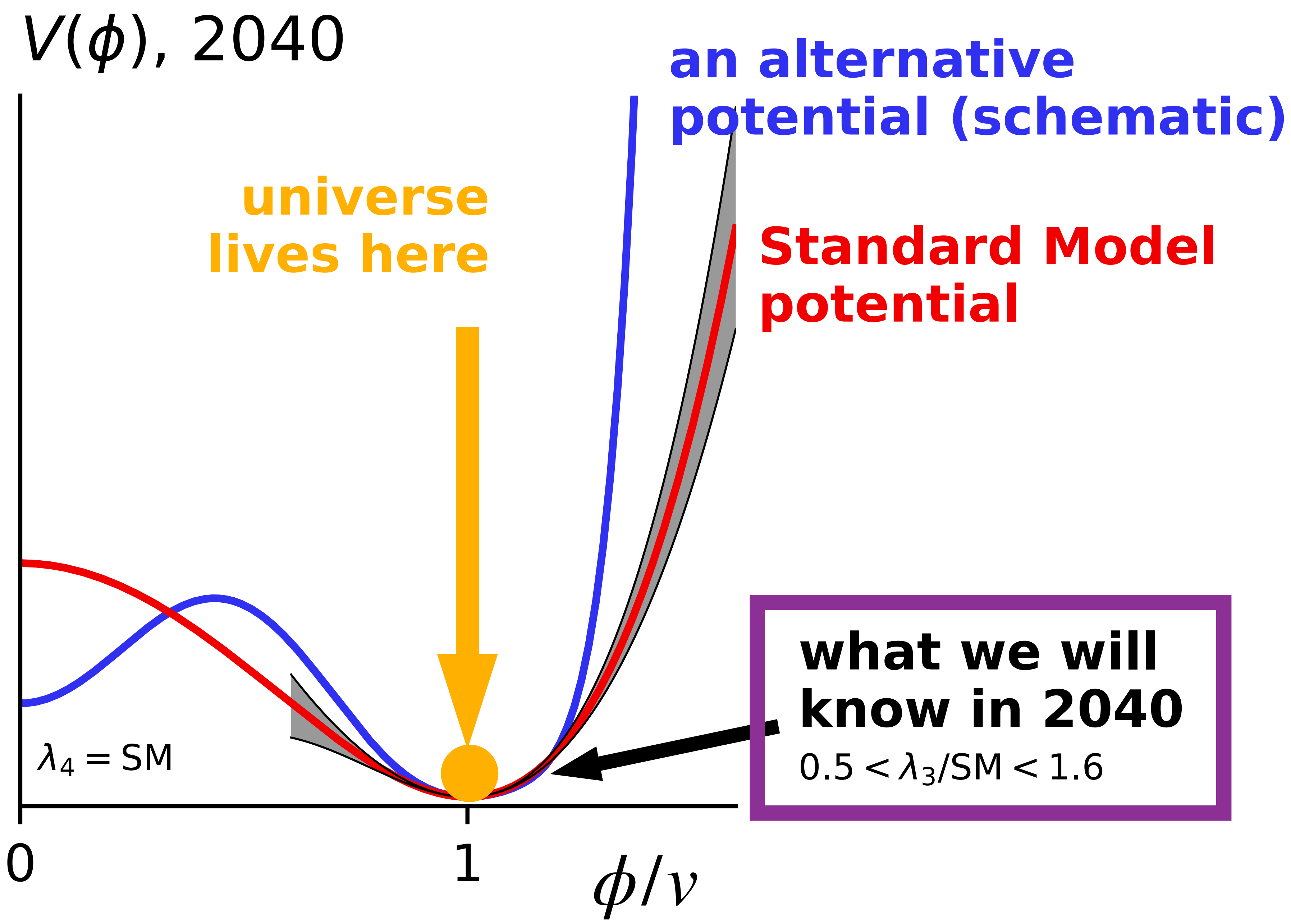
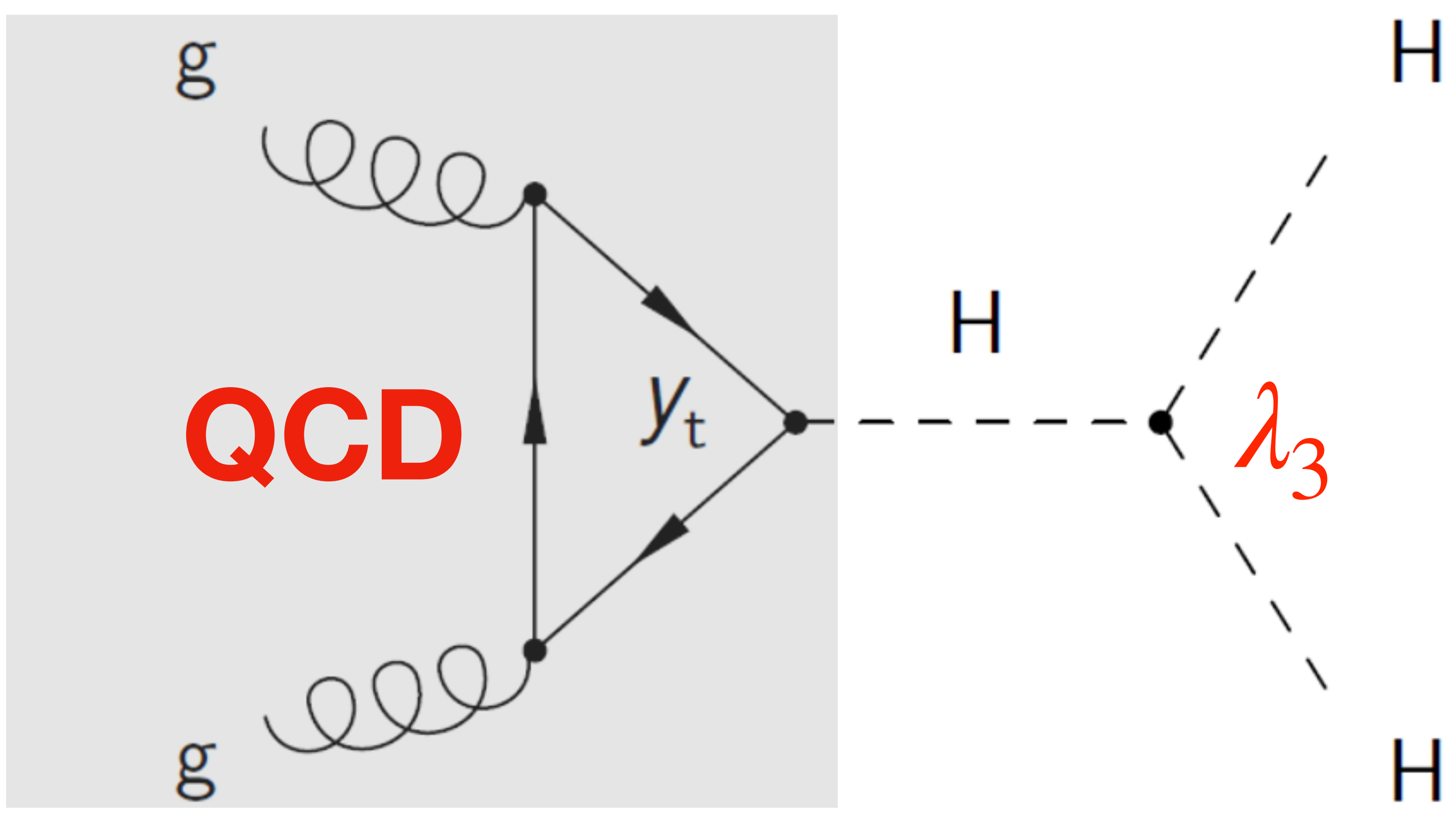
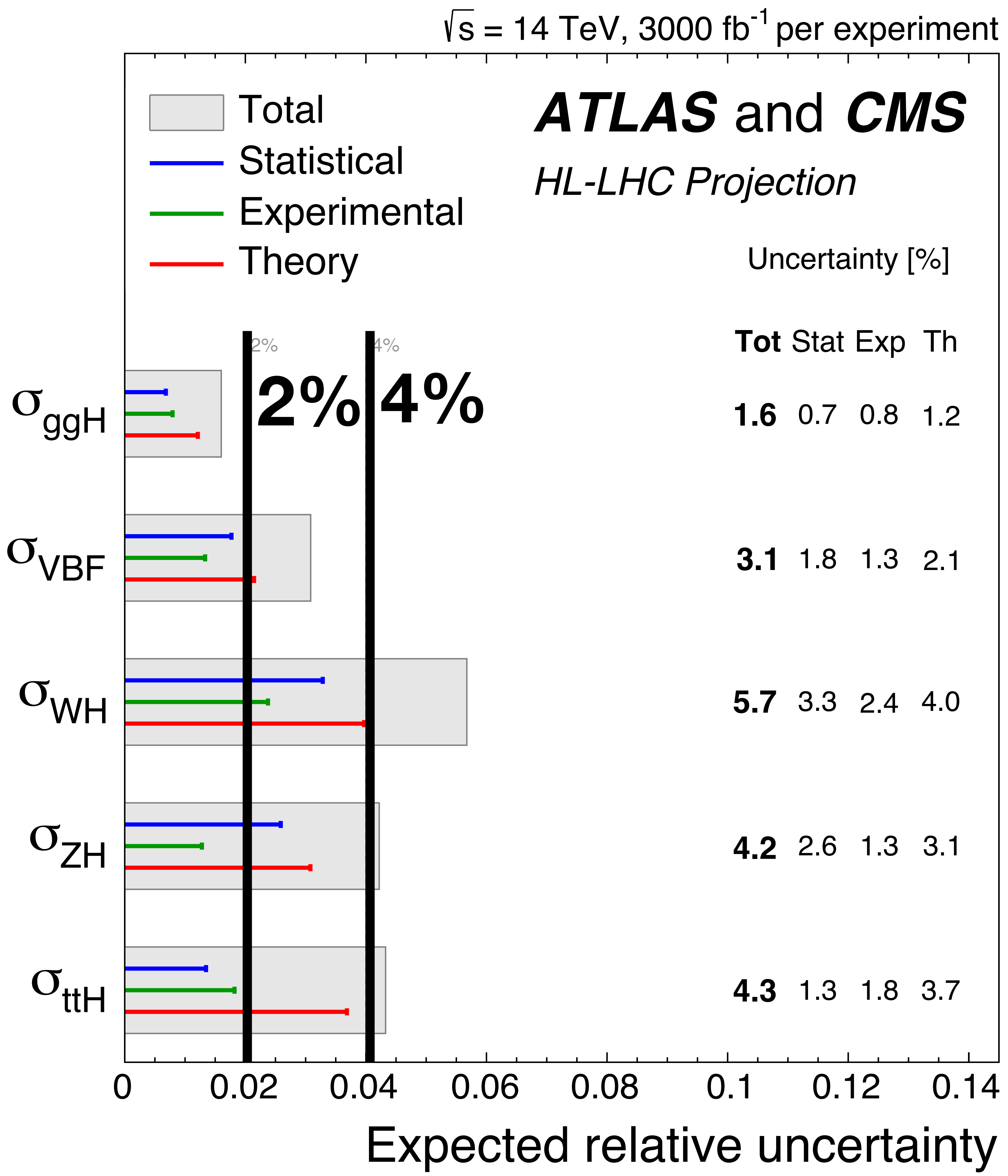


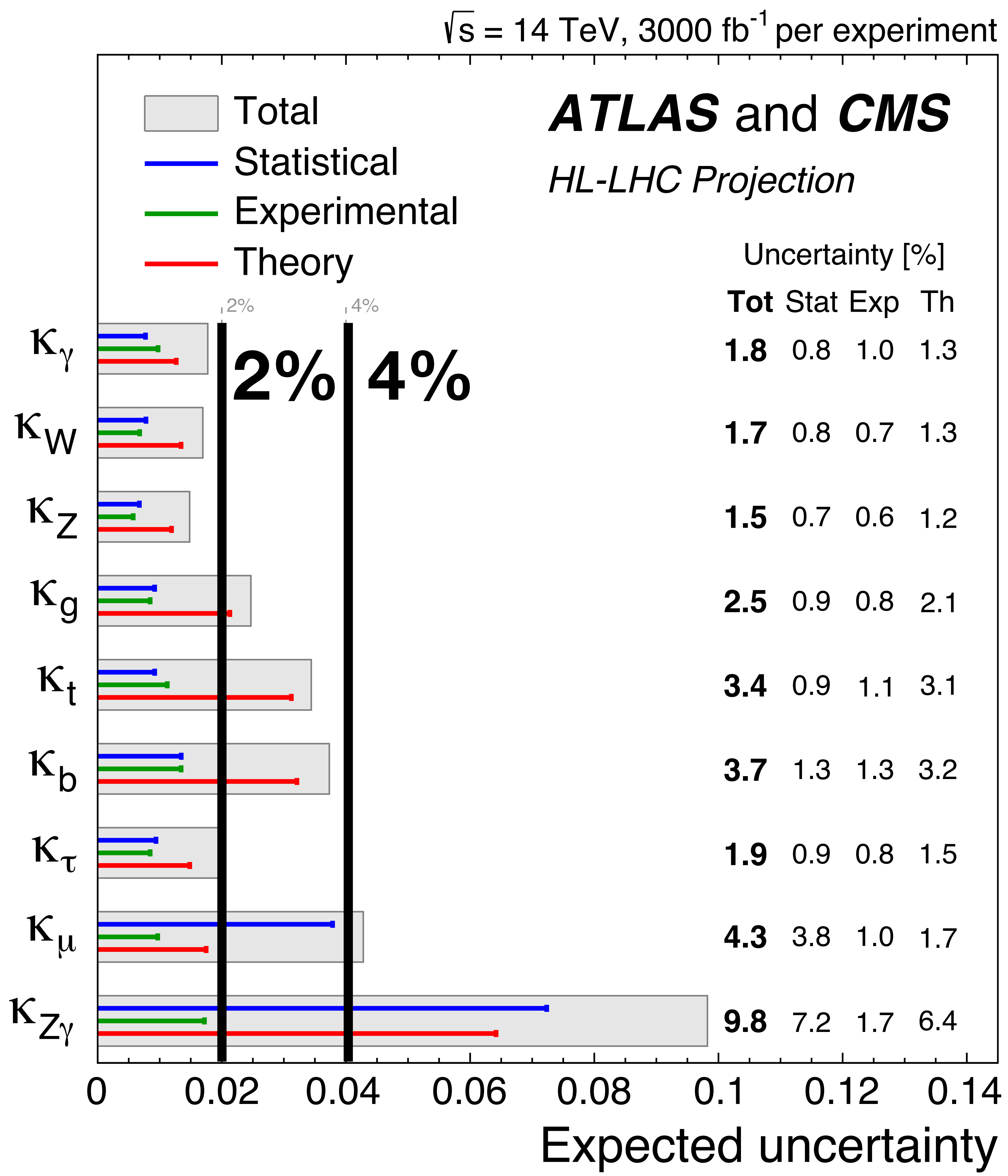
[Salam, Wang, Zanderighi, Nature 607 (2022) 7917, 41-47]
[ATLAS-PHYS-PUB-2022-018]



HL-LHC will constraint λ_3

Precision frontier with the HL-LHC: e.g. single Higgs production

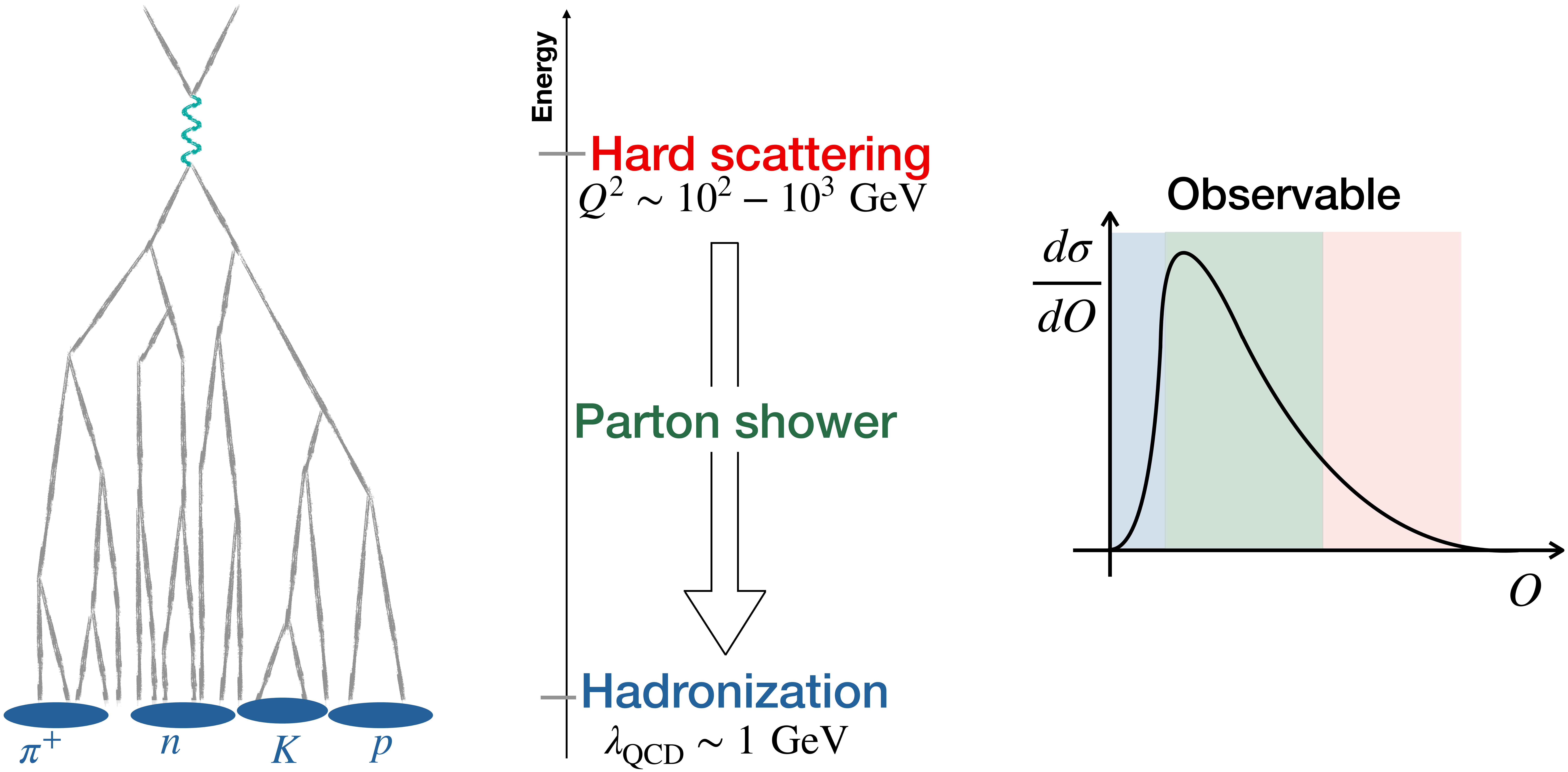




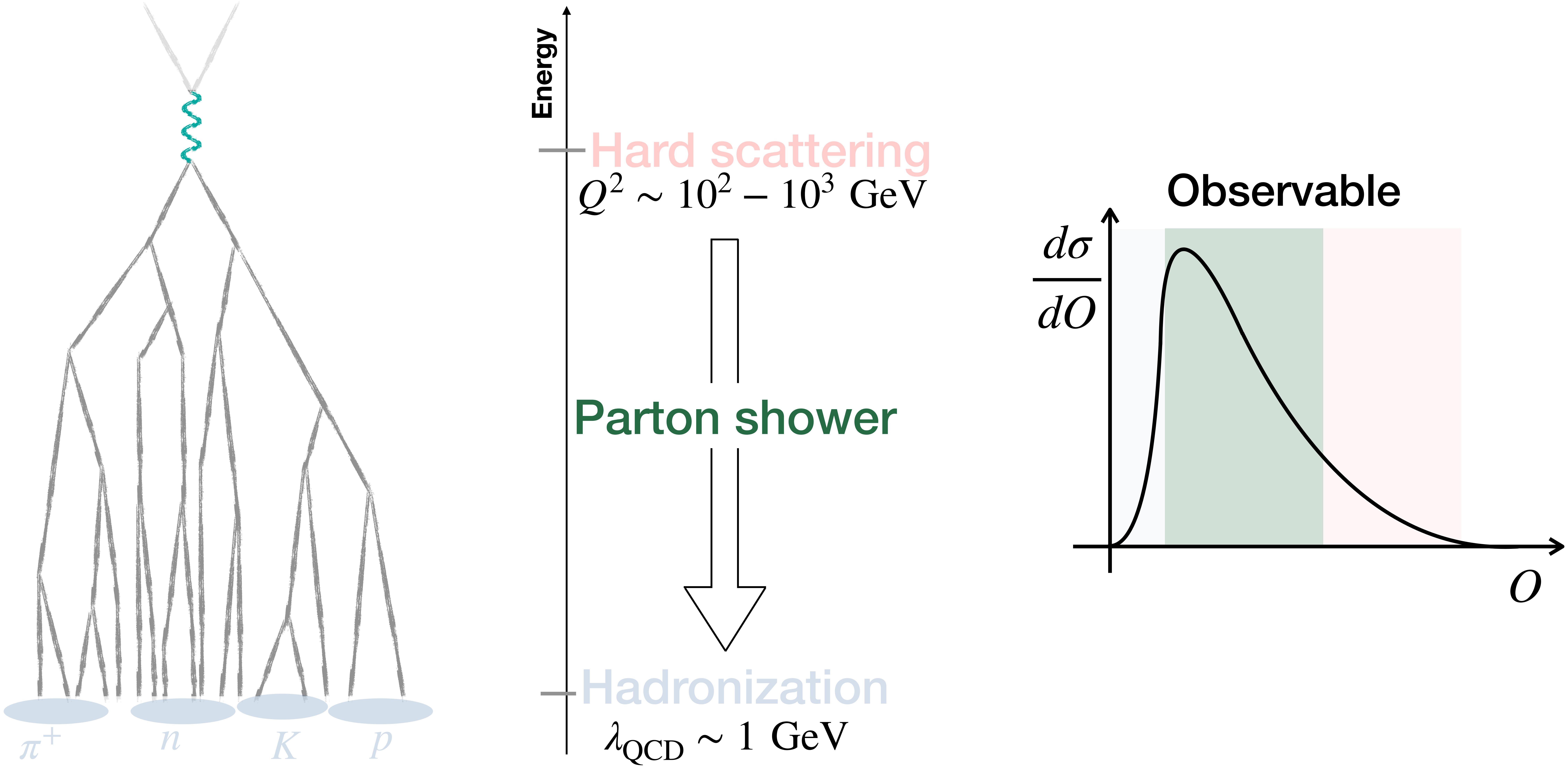
[ATLAS-PHYS-PUB-2022-018]

Theoretical predictions must achieve ~1%-accuracy

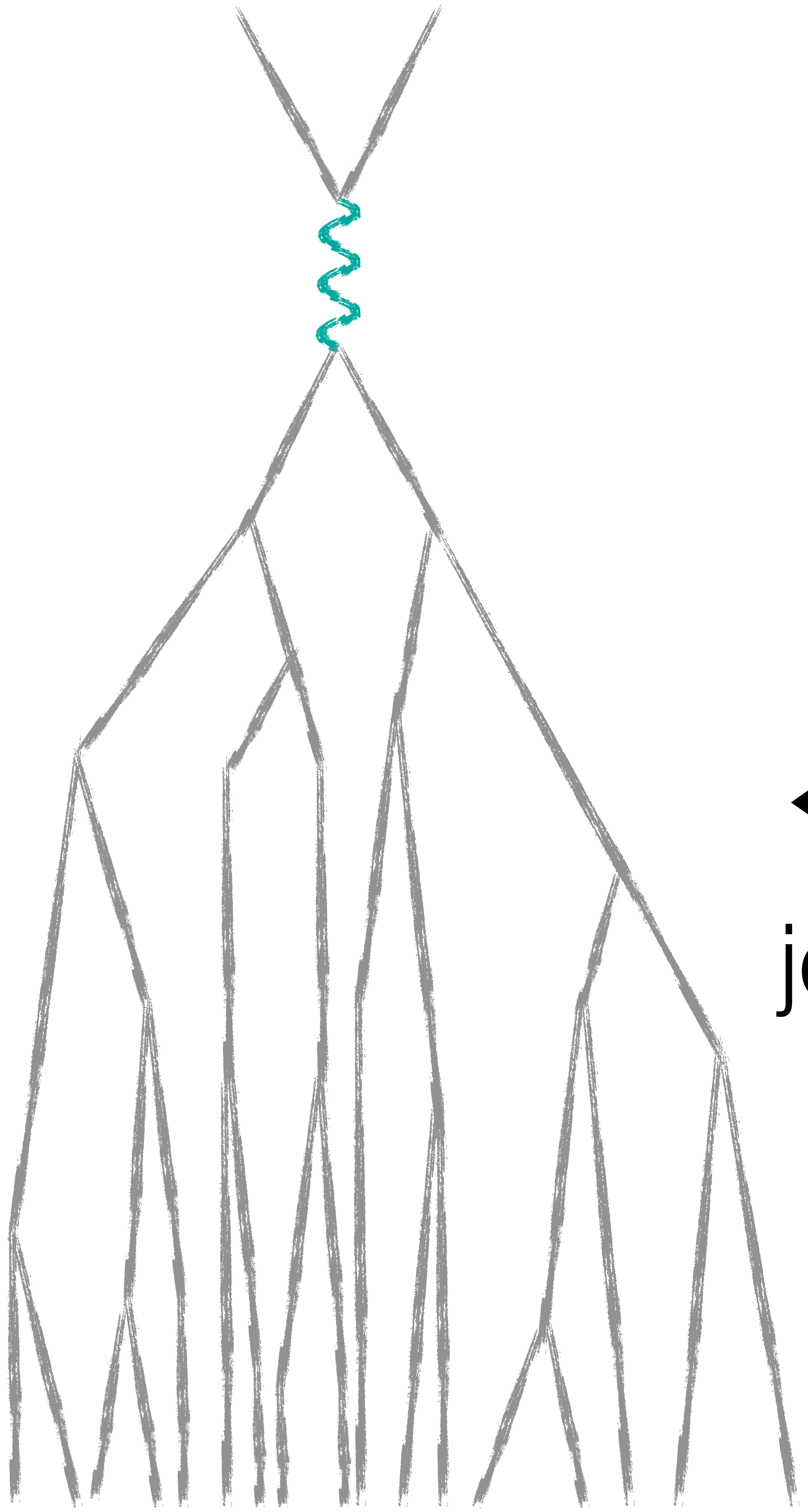
Anatomy of a high-energy process



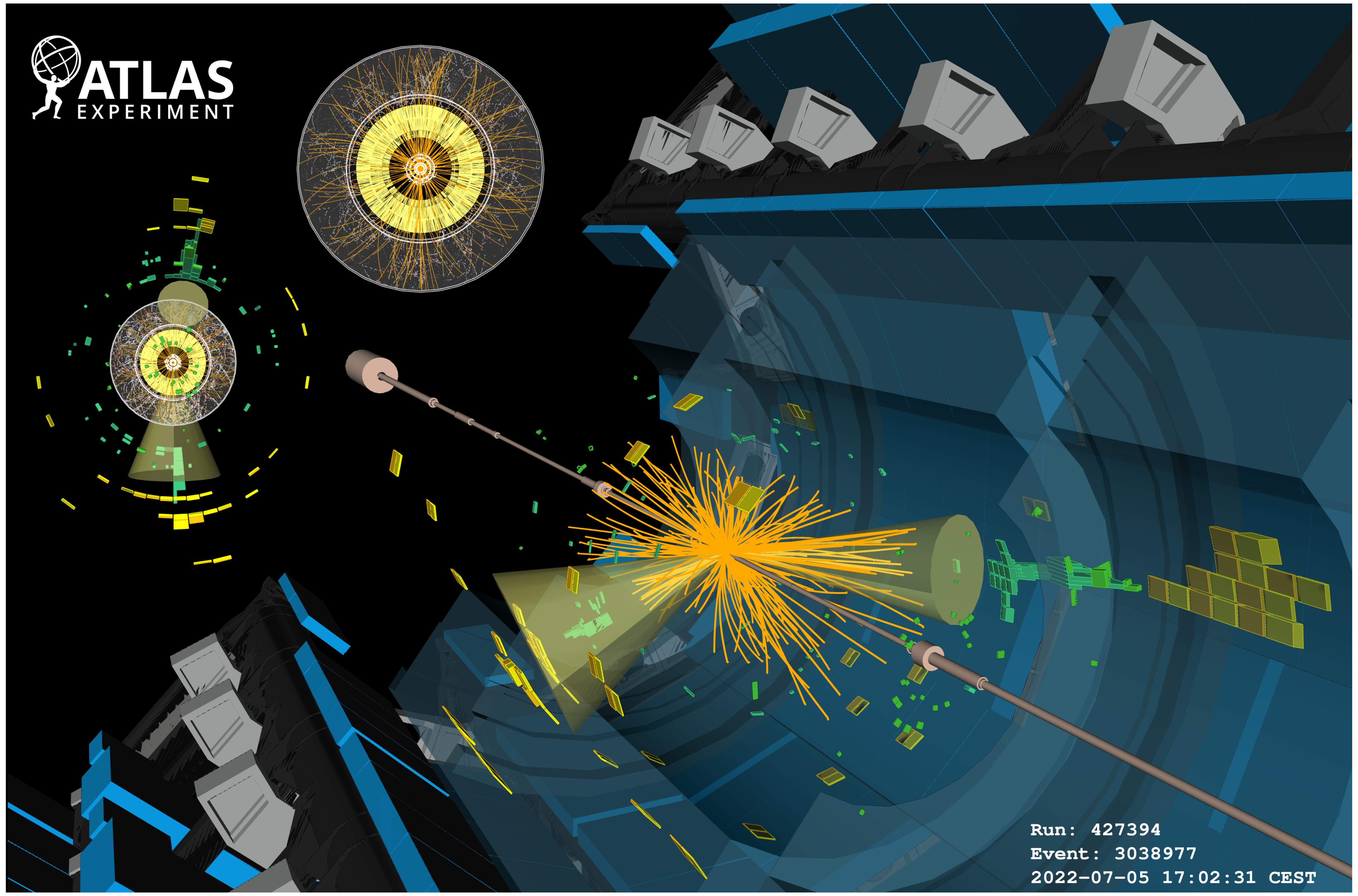
Anatomy of a high-energy process



Accessing parton branchings with LHC data



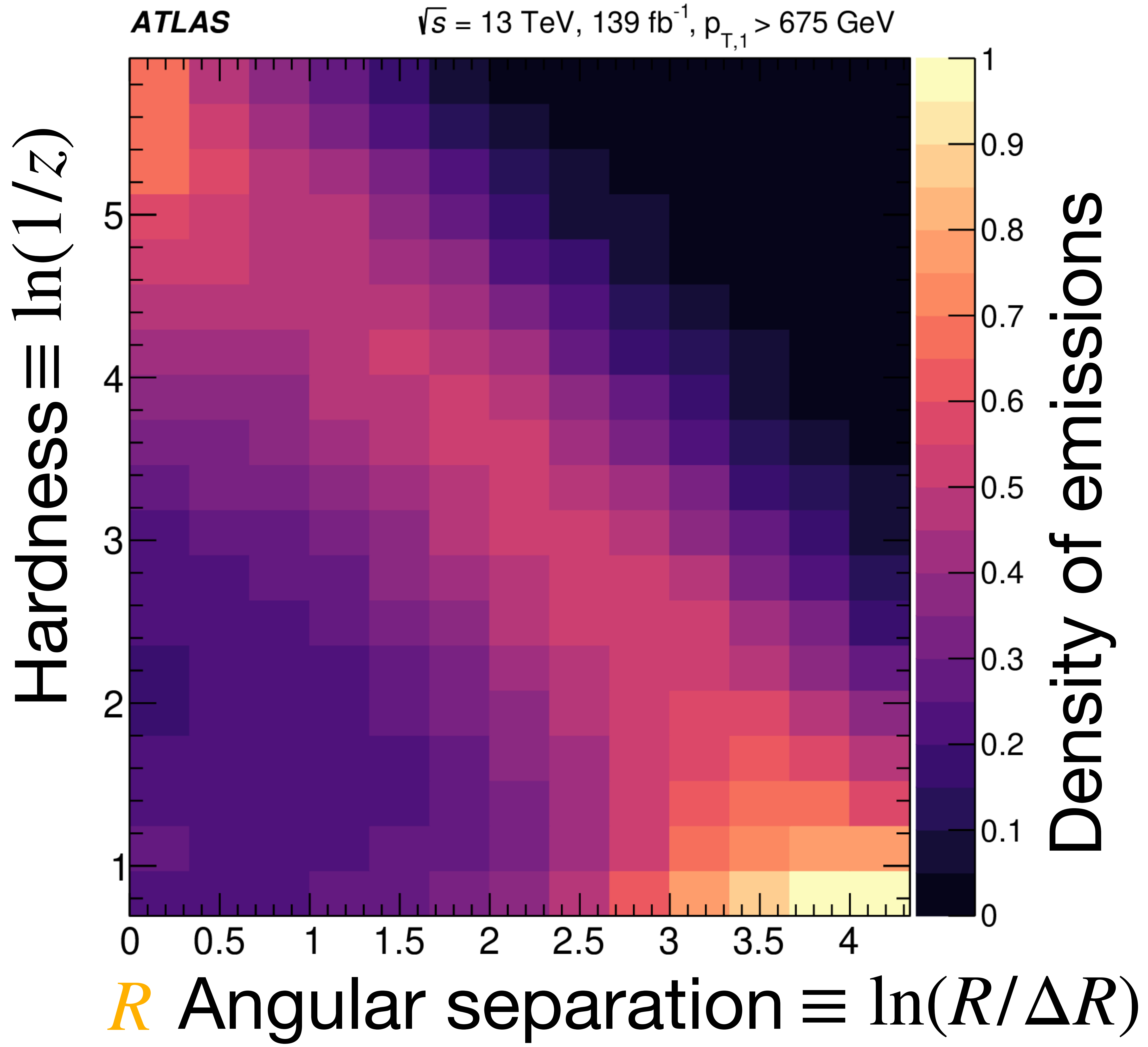
jet algorithms

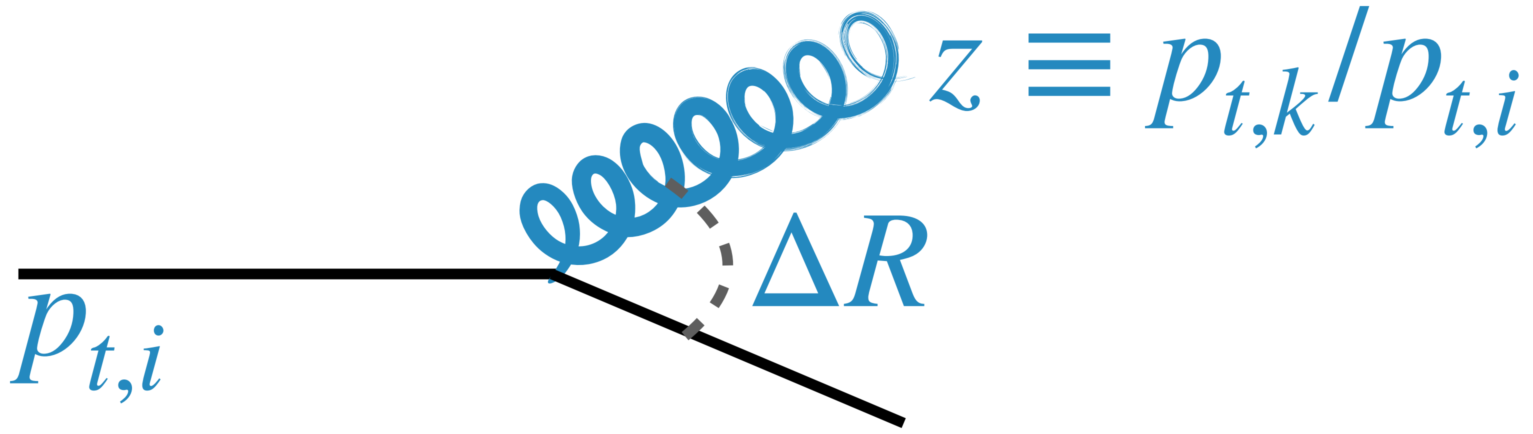


The LHC provides a multi-scale test of QCD evolution

Accessing parton branchings with LHC data

[ATLAS PRL 124 (2020) 22, 222002]

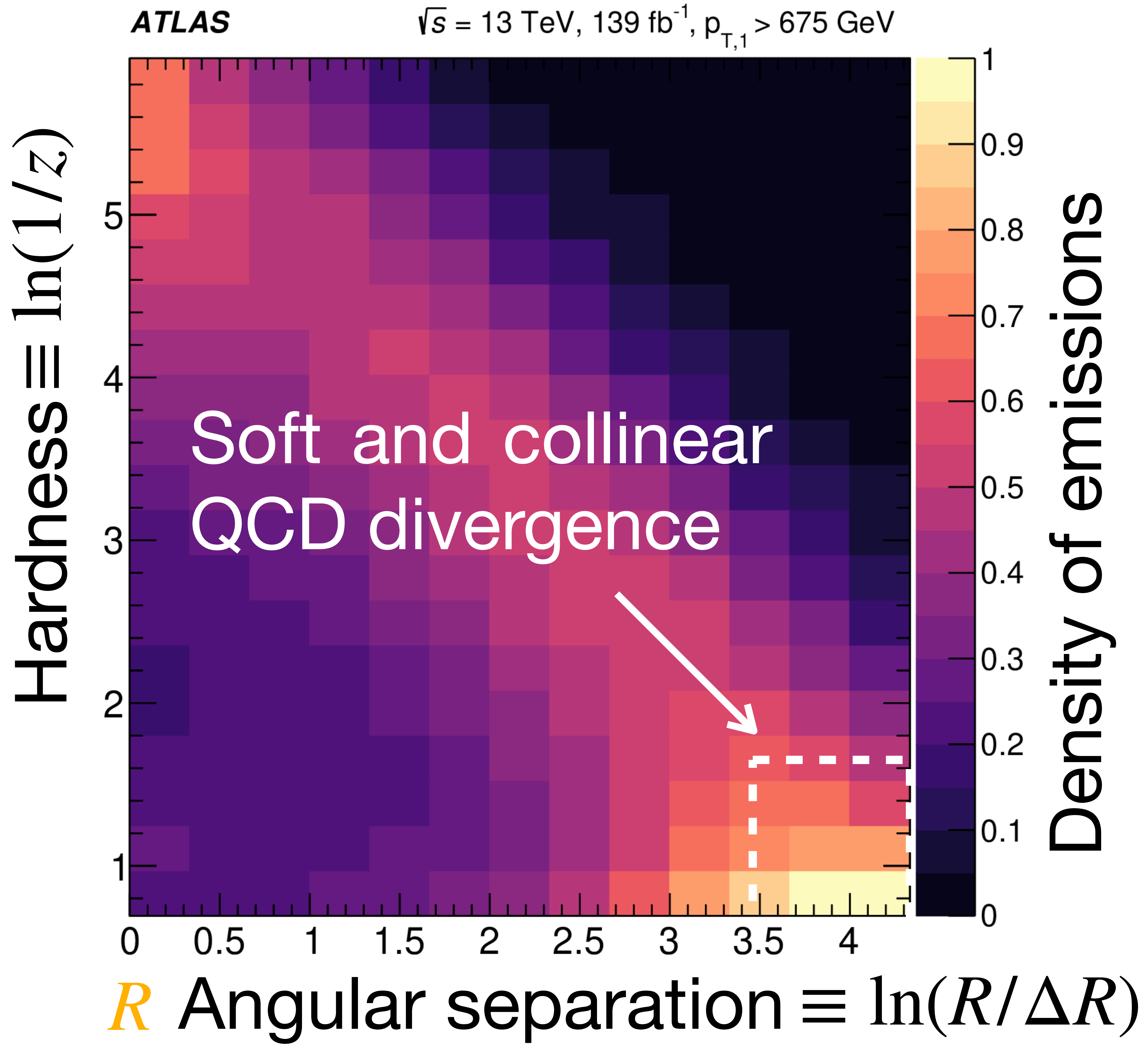




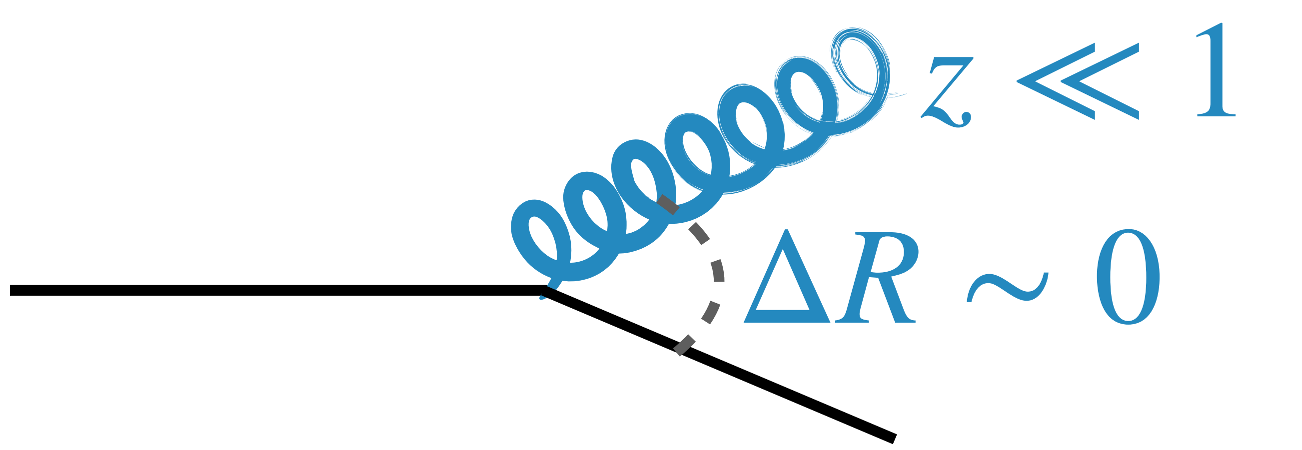
The phase-space of QCD branchings has a rich structure

Accessing parton branchings with LHC data

[ATLAS PRL 124 (2020) 22, 222002]



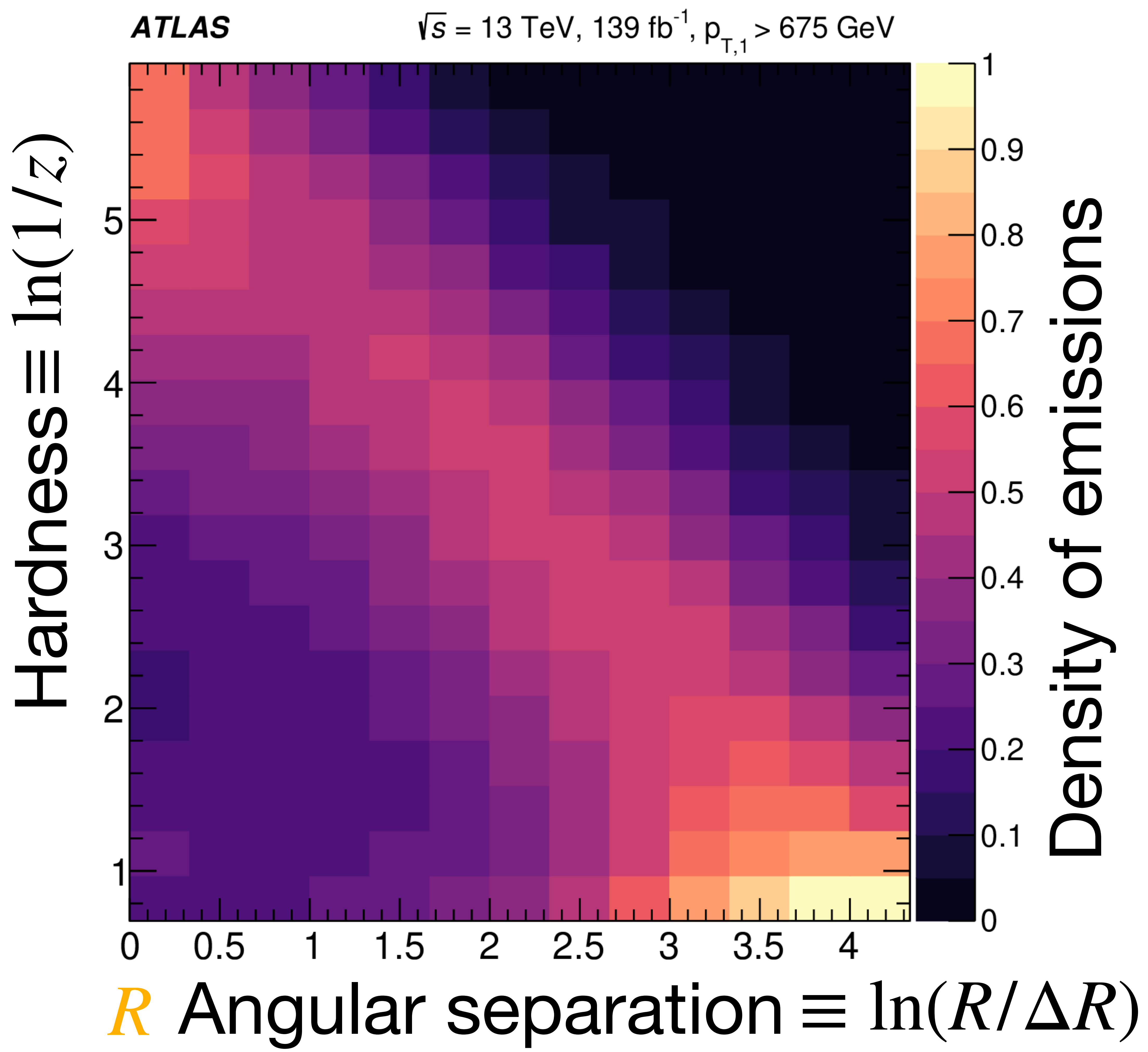
Distinguishing features of QCD exposed to the naked eye



$$P_{i\to jk} \propto \ln(1/\Delta R)\ln(1/z)$$

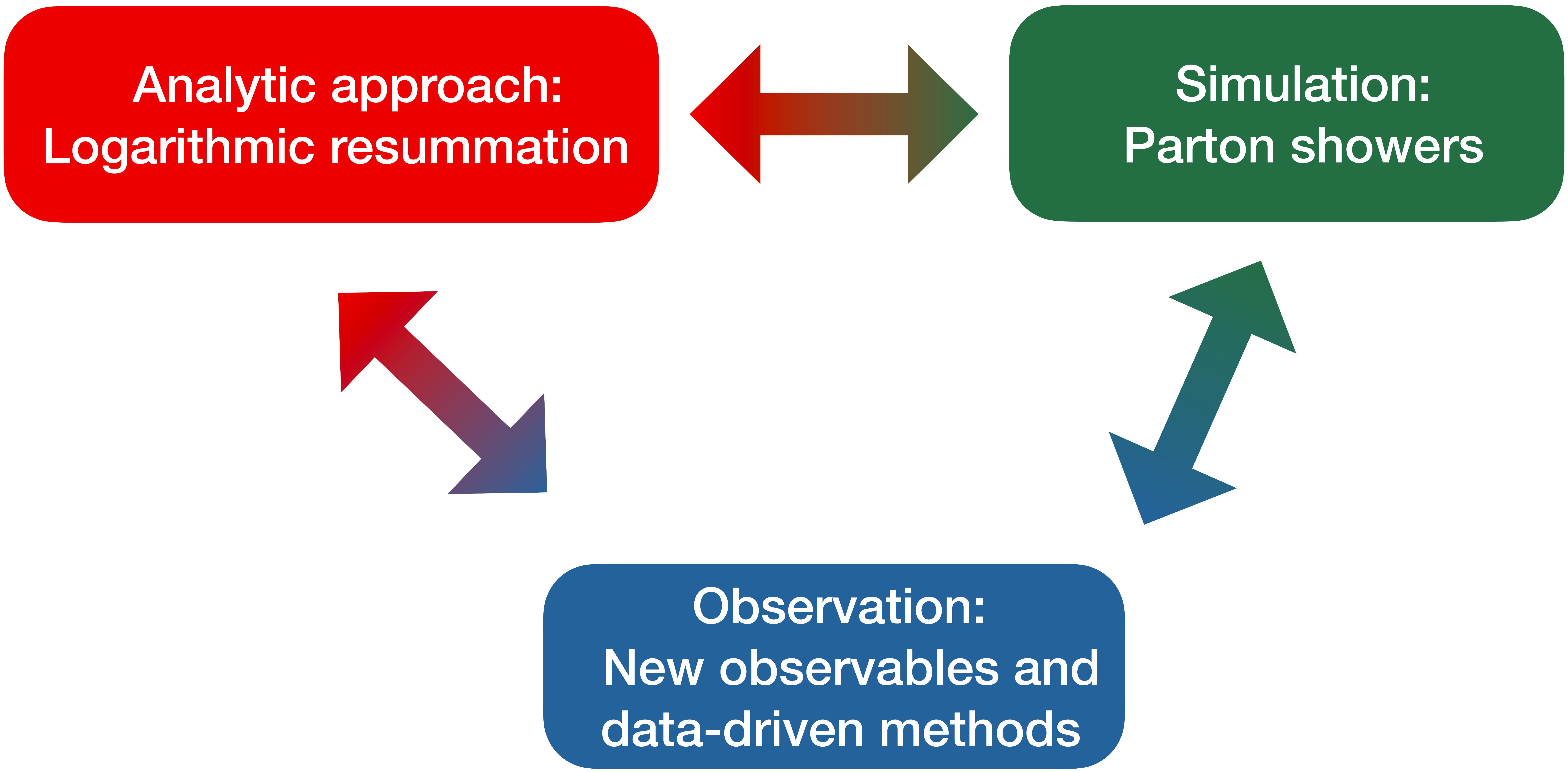
Accessing parton branchings with LHC data

[ATLAS PRL 124 (2020) 22, 222002]

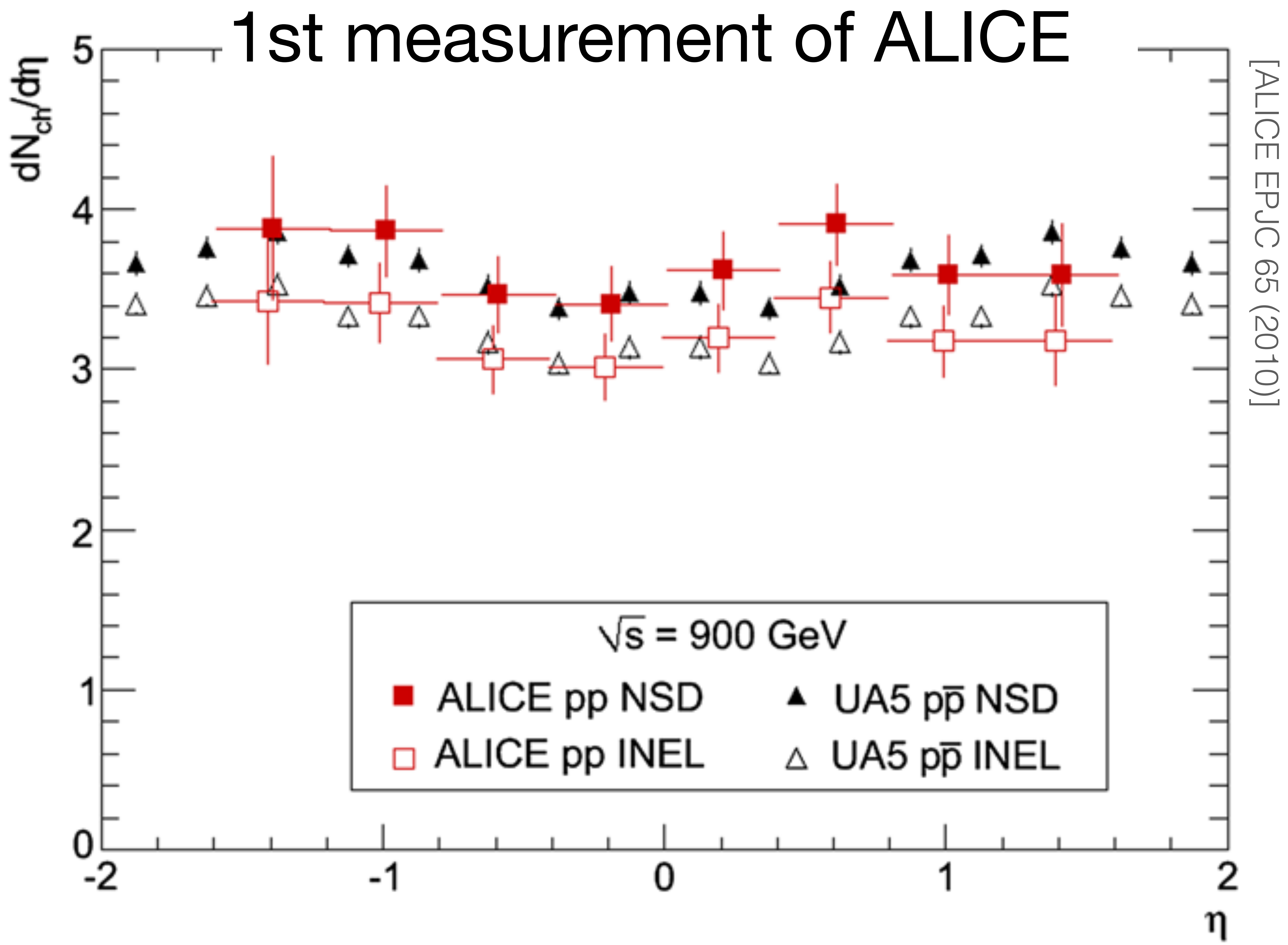


Goal: improve our theoretical understanding of QCD branchings

Outline of this talk



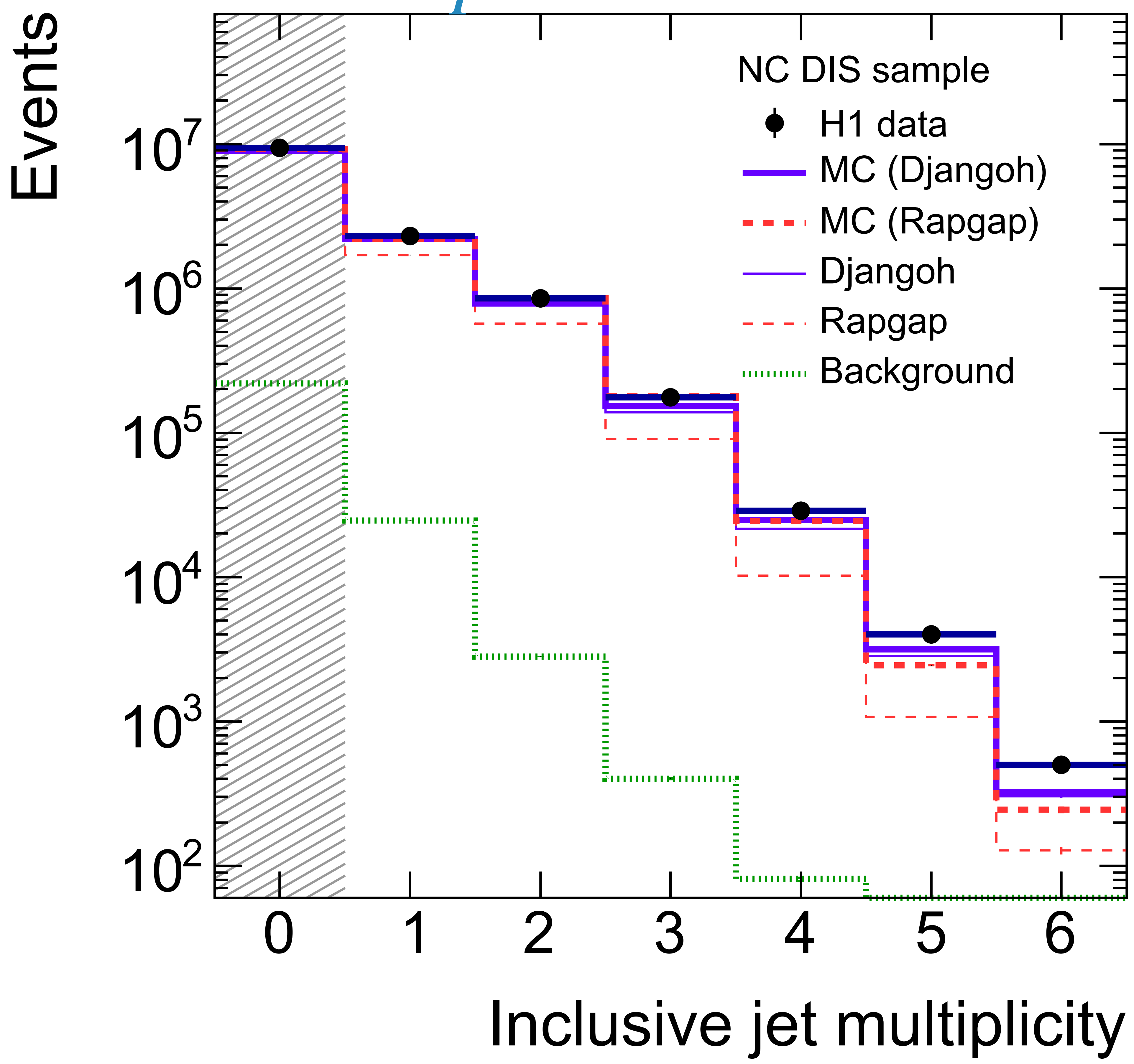
Multiplicity: one of the most studied observables in colliders



Particle multiplicities are non-perturbative objects

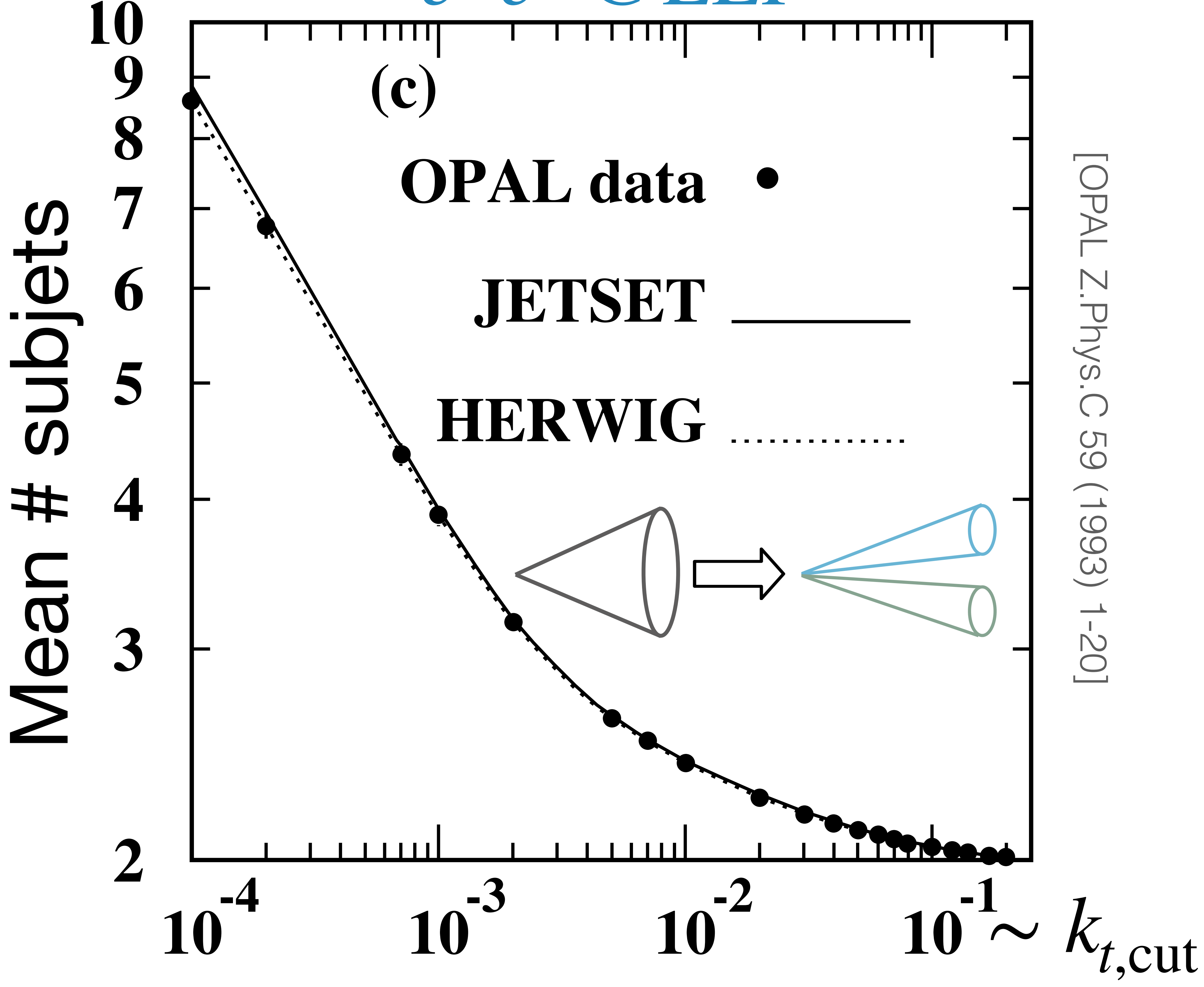
Multiplicity: one of the most studied observables in colliders

ep@HERA



[H1 Eur.Phys.J.C 77 (2017) 4, 215]

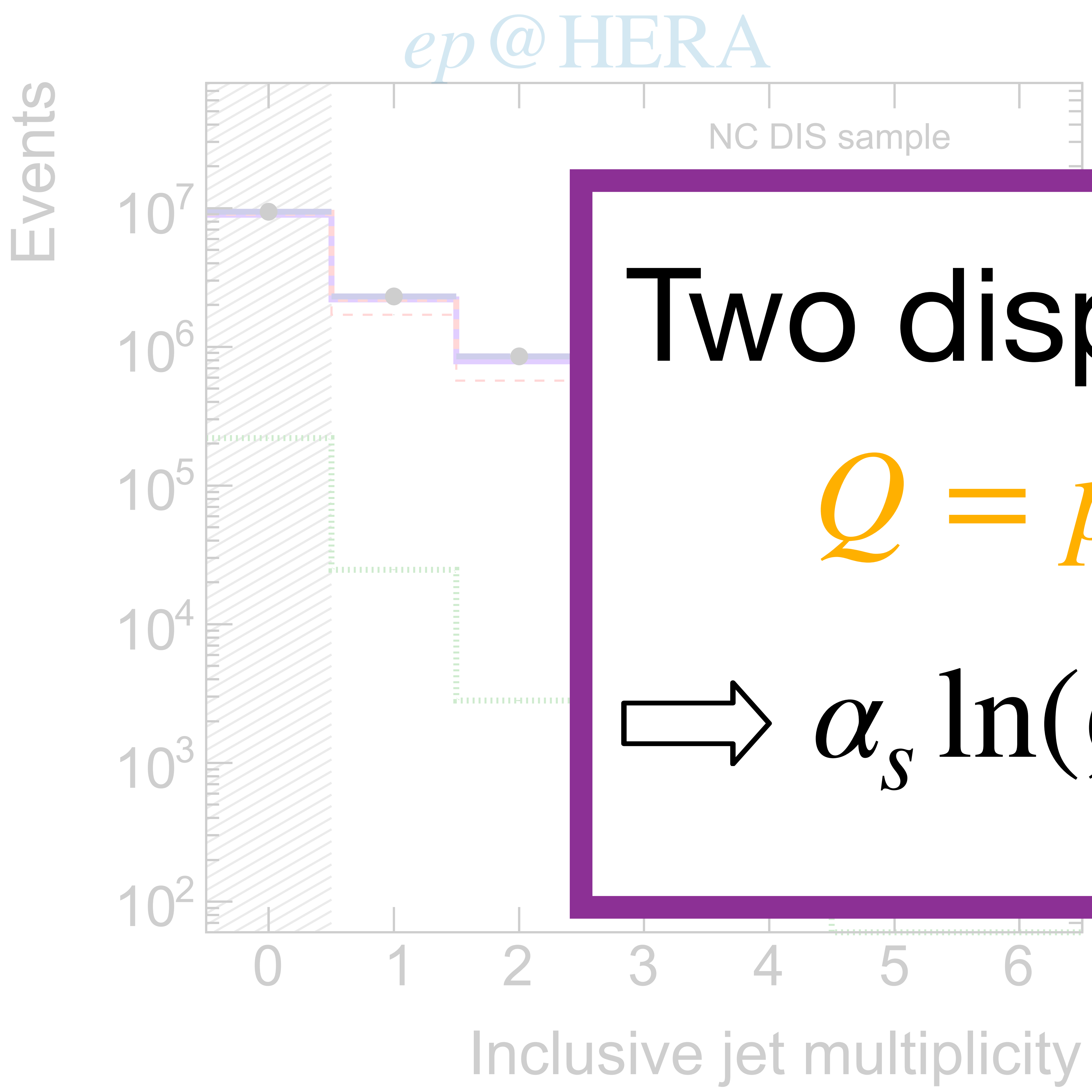
e^+e^-@LEP

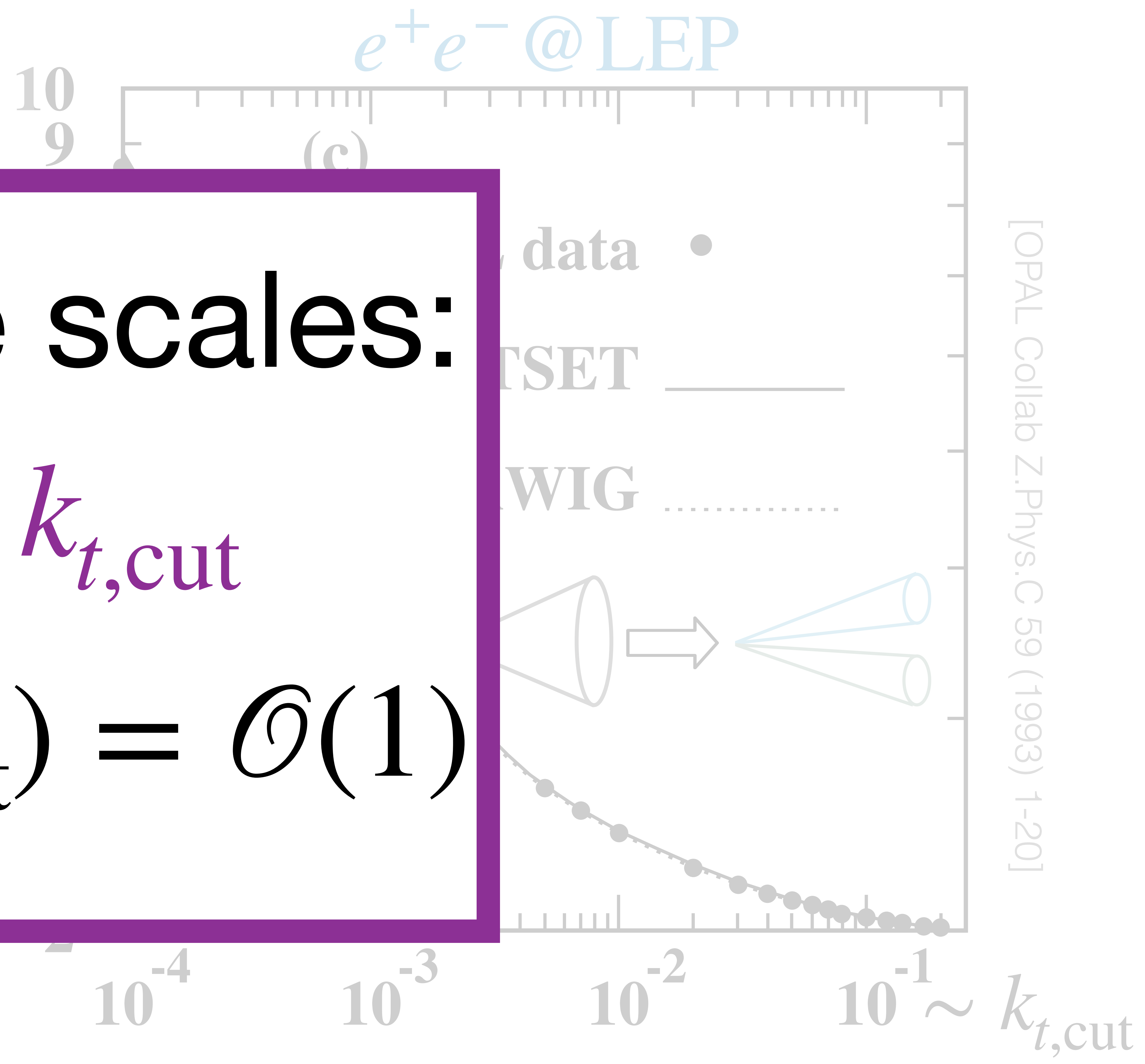


[OPAL Z.Phys.C 59 (1993) 1-20]

(Sub)jet multiplicities are calculable in pQCD $N(\alpha_s, Q, k_{t,\text{cut}})$

Multiplicity: one of the most studied observables in colliders





Two disparate scales:

$$Q = p_{t,\mathrm{jet}} R \ , \ k_{t,\mathrm{cut}}$$

$$\Longrightarrow \alpha_s \ln(Q/k_{t,\mathrm{cut}}) = \mathcal{O}(1)$$

(Sub)jet multiplicities are calculable in pQCD $N(\alpha_s, Q, k_{t,\mathrm{cut}})$

Analytic structure of the average subjet multiplicity

The perturbative expansion of the average subjet multiplicity reads

$$\langle N(\alpha_s; L)\rangle \underset{\substack{\alpha_s \ll 1 \\ \alpha_s L^2 \sim 1}}{=} \Big[\underbrace{h_1(\alpha_s L^2)}_{\text{DL}} + \underbrace{\sqrt{\alpha_s}\, h_2(\alpha_s L^2)}_{\text{NDL}} + \underbrace{\alpha_s h_3(\alpha_s L^2)}_{\text{NNDL}\sim 10\%} + \ldots\Big]$$

where $\mathrm{N}^k\mathrm{DL}$ accuracy implies control over $\alpha_s^n L^{2n-k}$ terms with $0 < n < \infty$

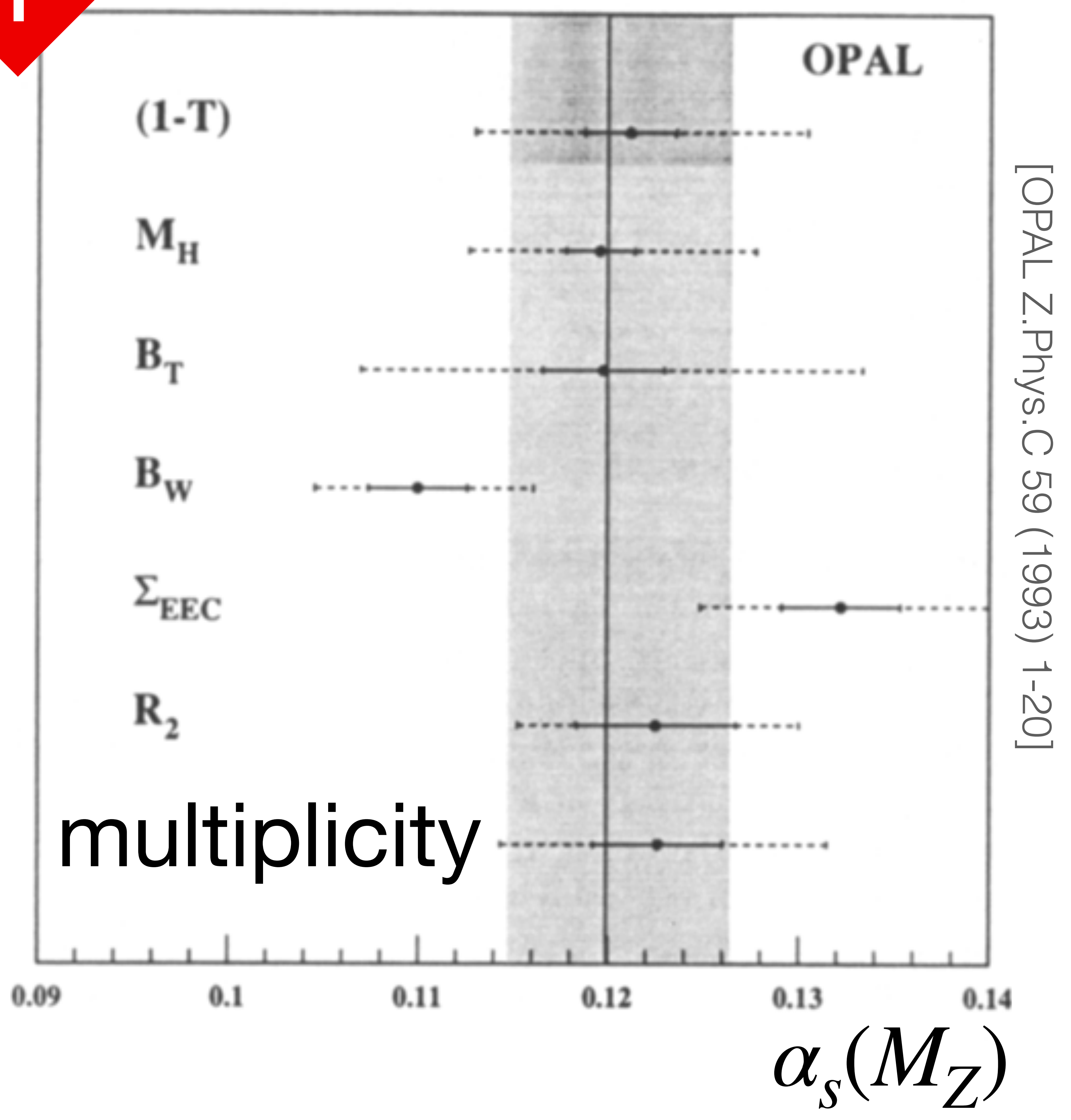
Goal: NNDL calculation of average subjet multiplicity

[Medves, ASO, Soyez, JHEP 10 (2022) 156, 2212.05076]

Motivations to push for higher accuracy

1

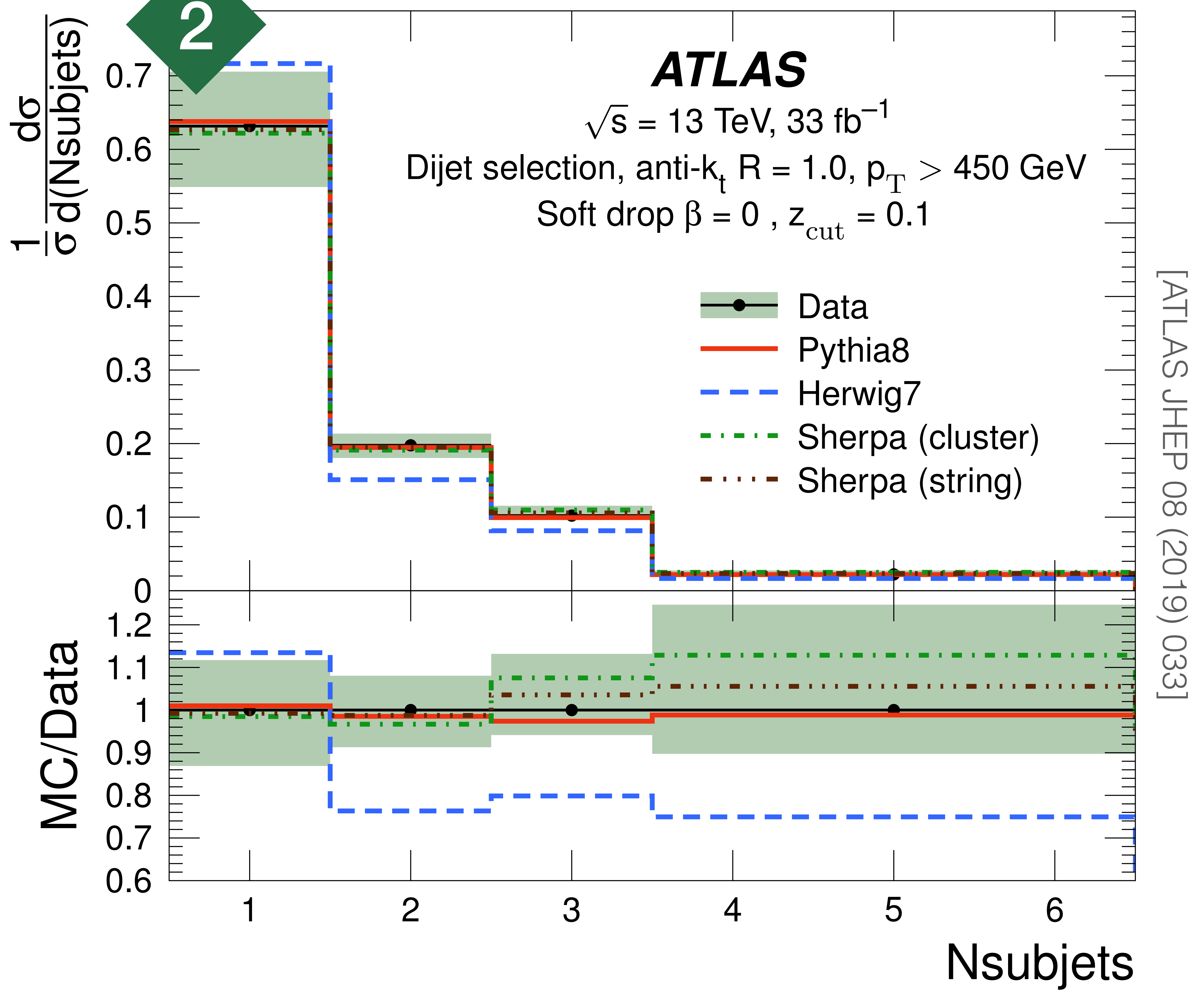
e^+e^-@LEP



[Catani, Dokshitzer, Fiorani, Webber NPB 377 (1992) 445-460]

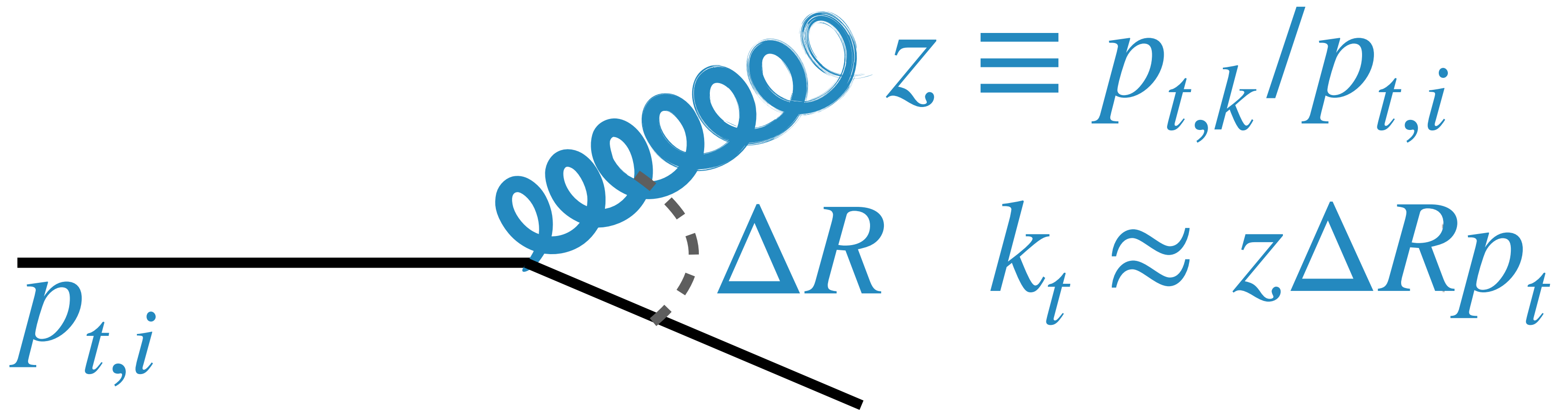
$\alpha_s(M_Z)$ extractions at e+e- colliders

2



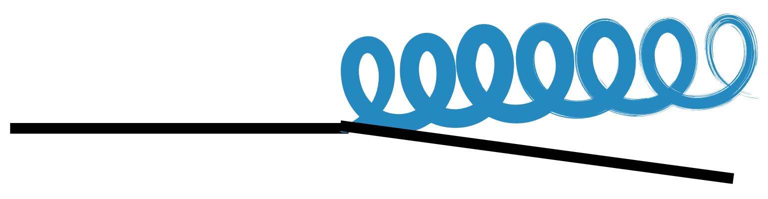
Calibrate MC generators

Average subjet multiplicity at DL: $(\alpha_s L^2)^n$

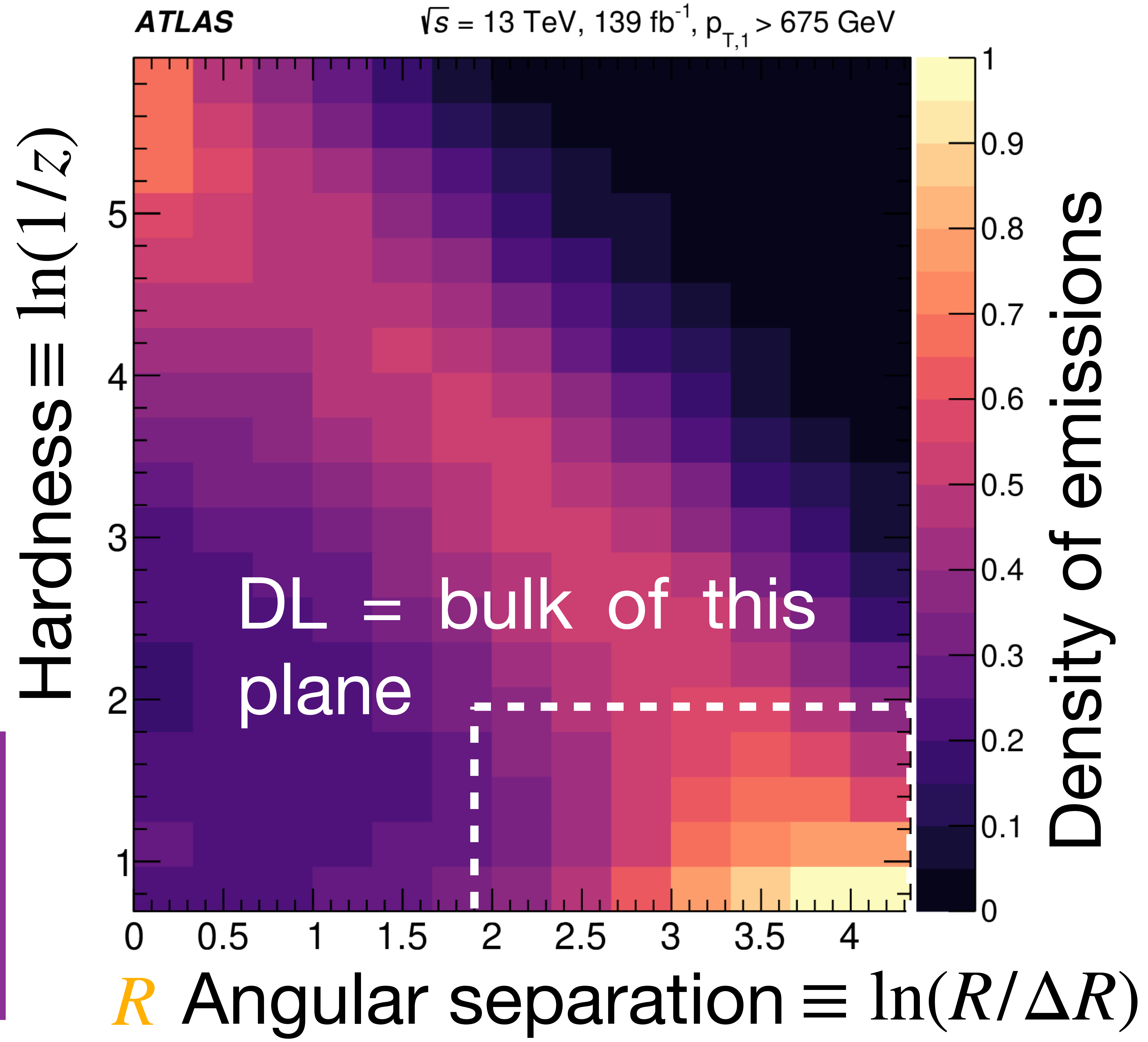


$$dP \to \alpha_s C_i \underbrace{\frac{dz}{z}\frac{d\theta}{\theta}}_{L^2}$$

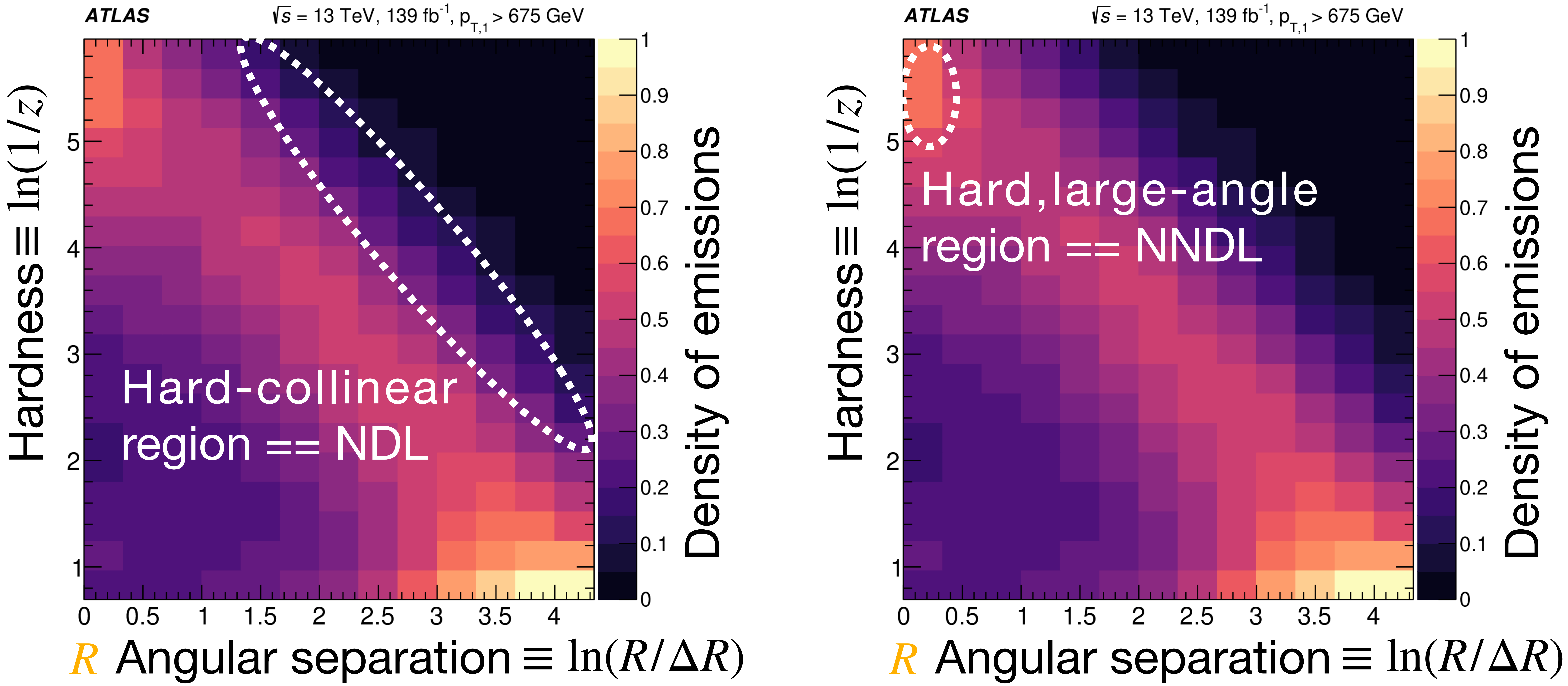
$$\langle N_i^{\mathrm{DL}} \rangle \propto \sum_{n=1}^{\infty}$$



$$\Theta(k_{tn} > k_{t,\mathrm{cut}})$$



Higher-orders == new phase-space regions at test



Average subjet multiplicity at DL and NDL

DL: $h_1^{(q)} = 1 + \frac{C_F}{C_A}(\cosh\nu - 1)$ $\qquad \nu = \sqrt{2\alpha_s C_A L^2/\pi}$

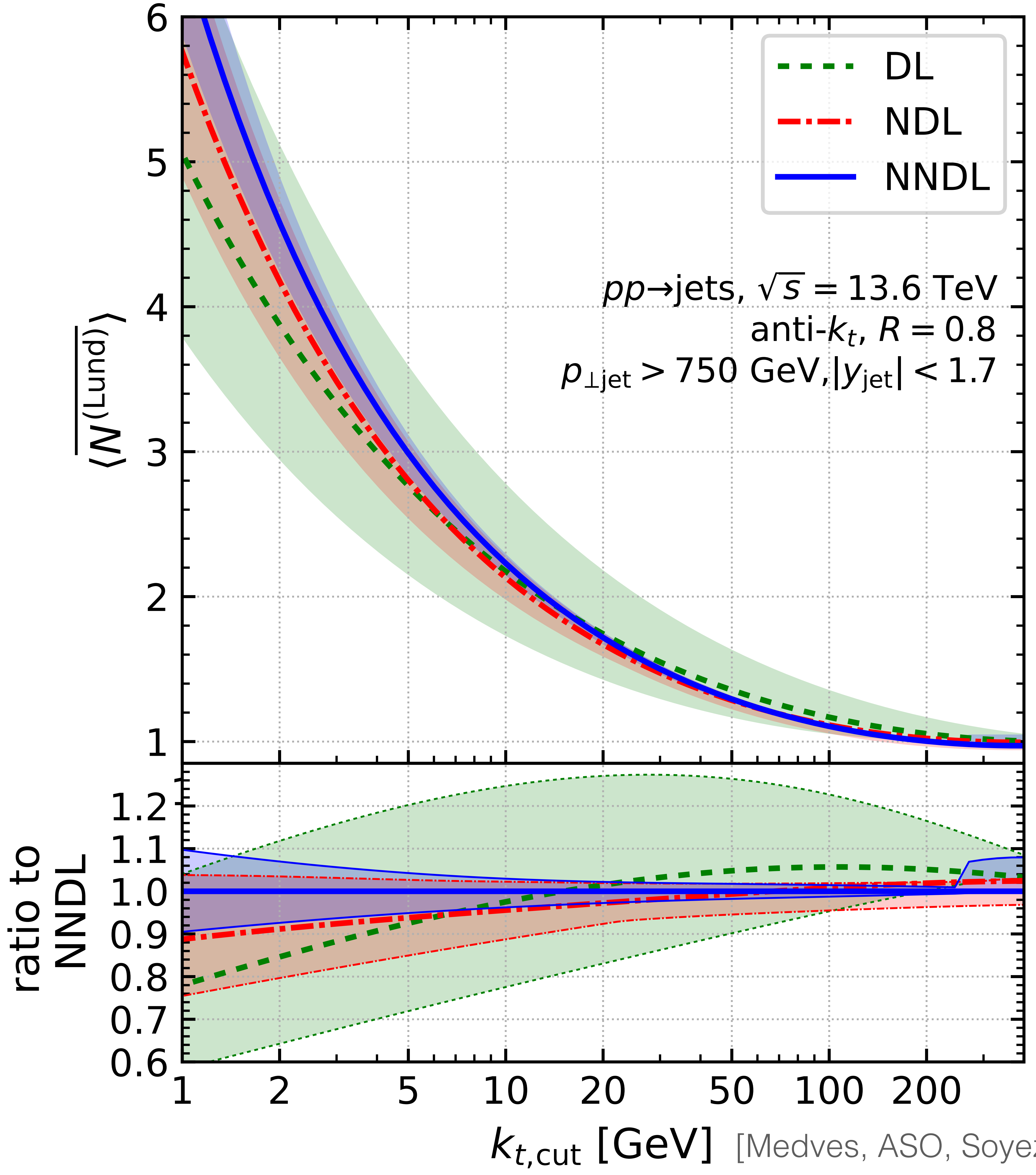
NDL: $h_2^{(q)} = \frac{C_F}{\sqrt{2\pi C_A}}\Big\{\frac{\pi\beta_0}{2C_A}\left[(\nu^2-1)\sinh\nu + \nu\cosh\nu\right] + (B_{gg} + c_\delta B_{gq})\nu\cosh\nu$

$+ \left[2B_q - B_{gg} + (2-3c_\delta)\,B_{gq}\right]\sinh\nu + 2(c_\delta - 1)B_{gq}\nu\Big\}$

Average subjet multiplicity at NNDL

NNDL:
$$
\begin{aligned}
2\pi h_3^{(q)} = {} & D_{\text{end}}^{q\to qg} + \left(D_{\text{end}}^{g\to gg} + D_{\text{end}}^{g\to q\bar{q}}\right)\frac{C_F}{C_A}(\cosh\nu - 1) + D_{\text{hme}}^{qqg}\cosh\nu \\
& + \frac{C_F}{C_A}\left[(1-c_\delta)D_{\text{pair}}^{q\bar{q}}(\cosh\nu - 1) + \left(K + D_{\text{pair}}^{gg} + c_\delta D_{\text{pair}}^{q\bar{q}}\right)\frac{\nu}{2}\sinh\nu\right] \\
& + C_F\left[\left(\cosh\nu - 1 - \frac{1-c_\delta}{4}\nu^2\right)D_{\text{clust}}^{(\text{prim})} + (\cosh\nu - 1)D_{\text{clust}}^{(\text{sec})}\right] \\
& + \frac{C_F}{C_A}\left[D_{\text{e-loss}}^{g}\frac{\nu}{2}\sinh\nu + (D_{\text{e-loss}}^{q} - D_{\text{e-loss}}^{g})(\cosh\nu - 1)\right] \\
& + \frac{C_F}{2}\Big\{(B_{gg} + c_\delta B_{gq})^2\nu^2\cosh\nu + 8\left[2c_\delta B_{gg} - 2c_\delta B_q - (1-3c_\delta^2)B_{gq}\right]B_{gq}\cosh\nu \\
& \qquad + \left[4B_q(B_{gg} + (2c_\delta + 1)B_{gq}) - (B_{gg} + c_\delta B_{gq})(B_{gg} + 9c_\delta B_{gq})\right]\nu\sinh\nu \\
& \qquad + 4(1-c_\delta^2)B_{gq}^2\nu^2 + 8\left[2c_\delta B_q - 2c_\delta B_{gg} + (1-3c_\delta^2)B_{gq}\right]B_{gq}\Big\} \\
& + \frac{C_F}{C_A}\frac{\pi\beta_0}{2}\Big\{(B_{gg} + c_\delta B_{gq})\nu^3\sinh\nu + \left[2B_q - 2B_{gg} + (6-8c_\delta)B_{gq}\right]\nu\sinh\nu \\
& \qquad + 2(B_q + B_{gg} + B_{gq})\nu^2\cosh\nu - 4(1-c_\delta)B_{gq}(2\cosh\nu - 2 + \nu^2)\Big\} \\
& + \frac{C_F}{C_A}\frac{\pi^2\beta_0^2}{8C_A}\left[3\nu(2\nu^2 - 1)\sinh\nu + (\nu^4 + 3\nu^2)\cosh\nu\right]
\end{aligned}
$$

The importance of higher logarithmic accuracy

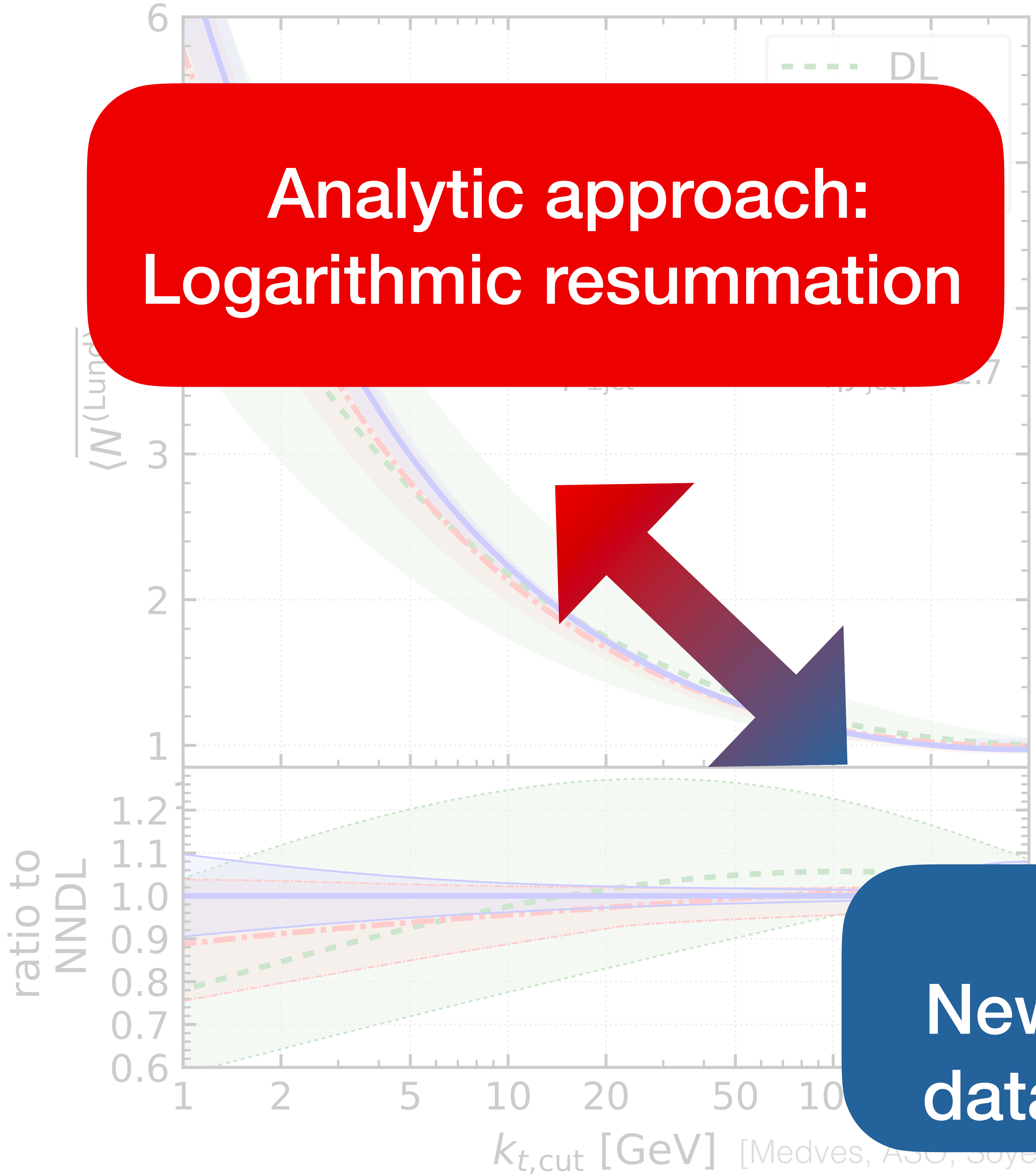


[Medves, ASO, Soyez 2212.05076]

The uncertainty of the theoretical prediction at $k_{t,\mathrm{cut}} = 5$ GeV is

DL: $28\,\%$, NDL: $10\,\%$, NNDL: $5\,\%$

The importance of higher logarithmic accuracy



[Medves, ASO, Soyez 2212.03076]

Analytic approach: Logarithmic resummation

Observation: New observables and data-driven methods

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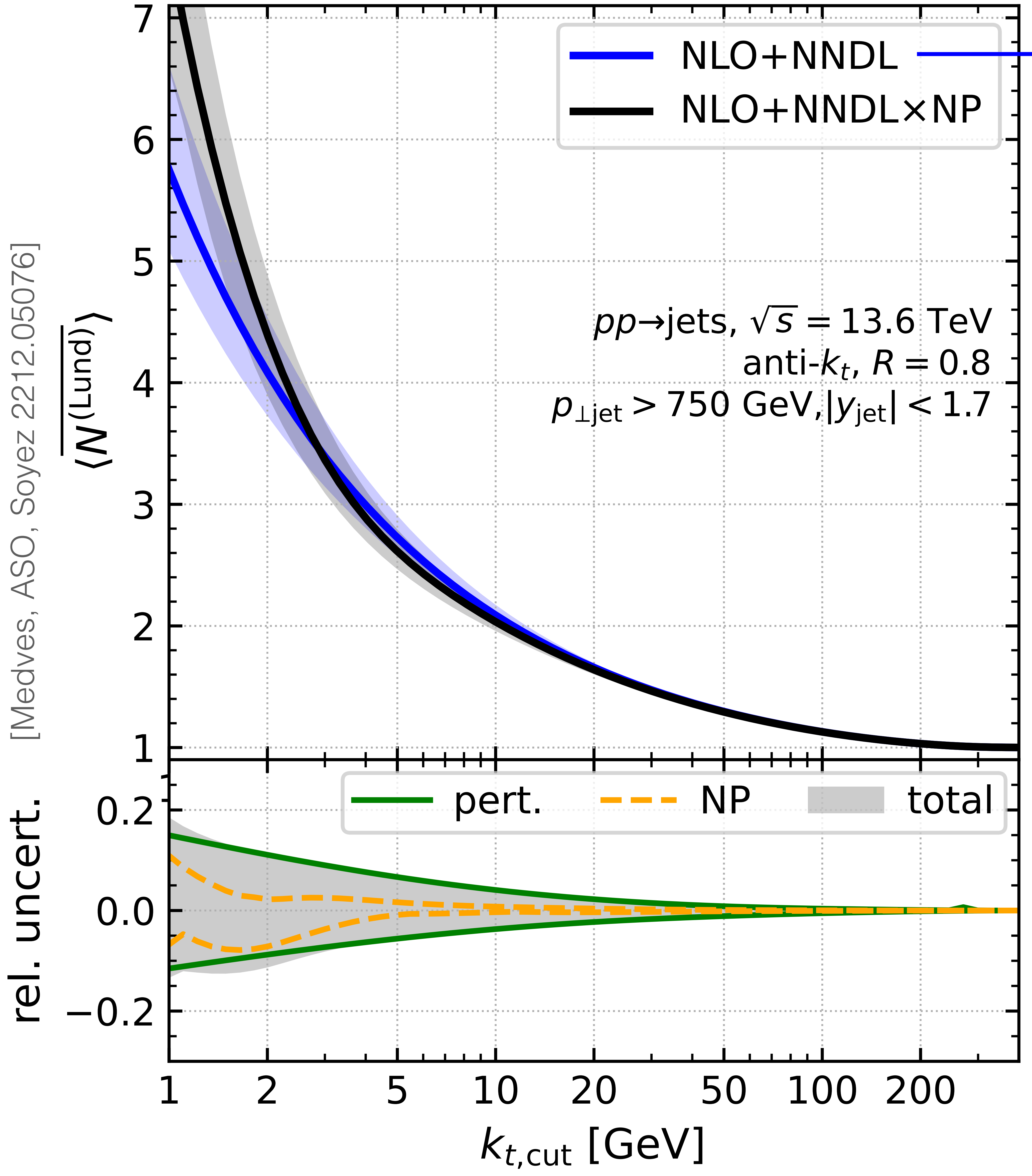
Lund multiplicity predictions for LHC jets



pure pQCD

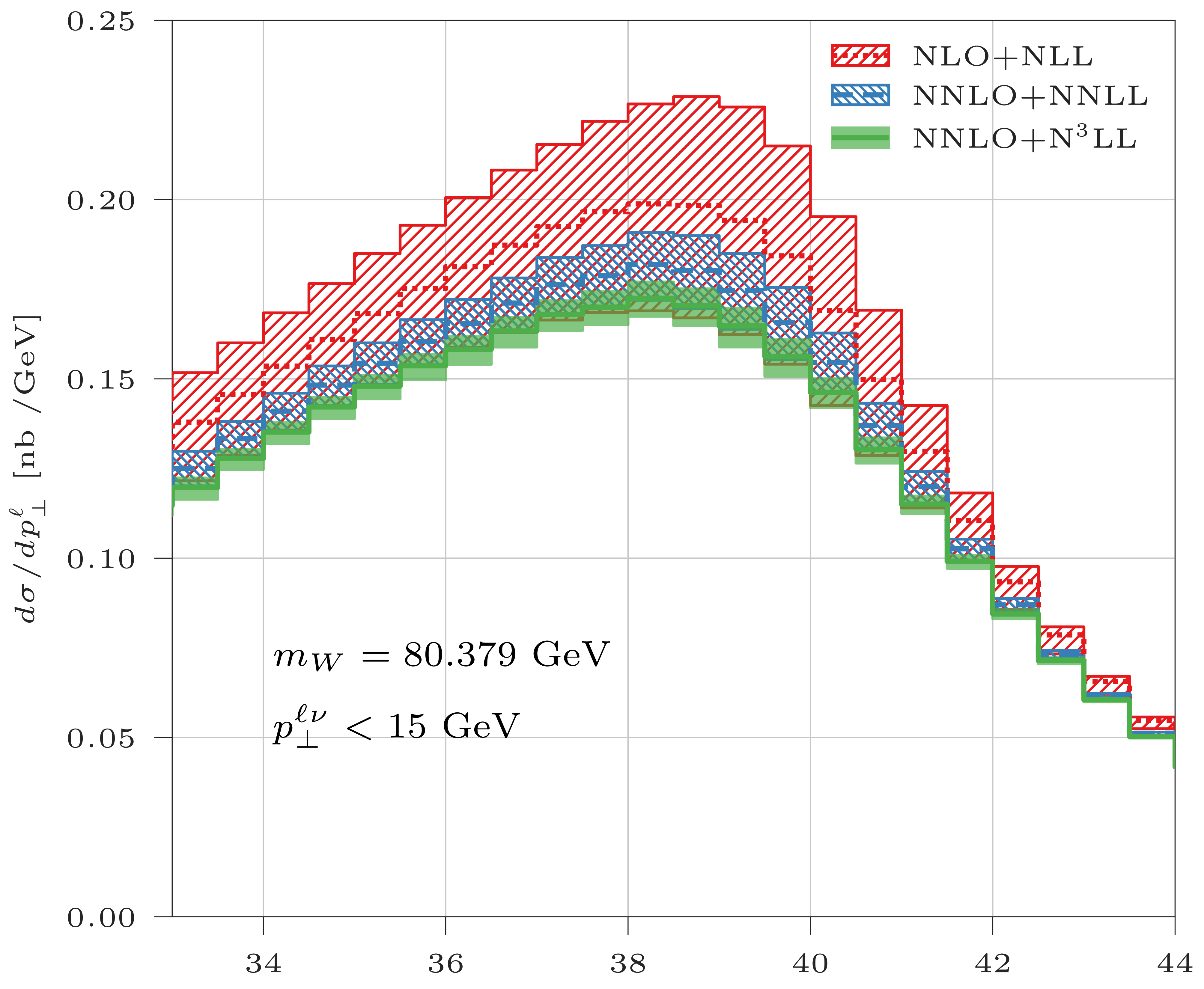
Non-perturbative corrections remain below 5% in a large region of $k_{t,\text{cut}}$

⇩

Good observable for robust theory-to-data (ATLAS, soon) comparisons.

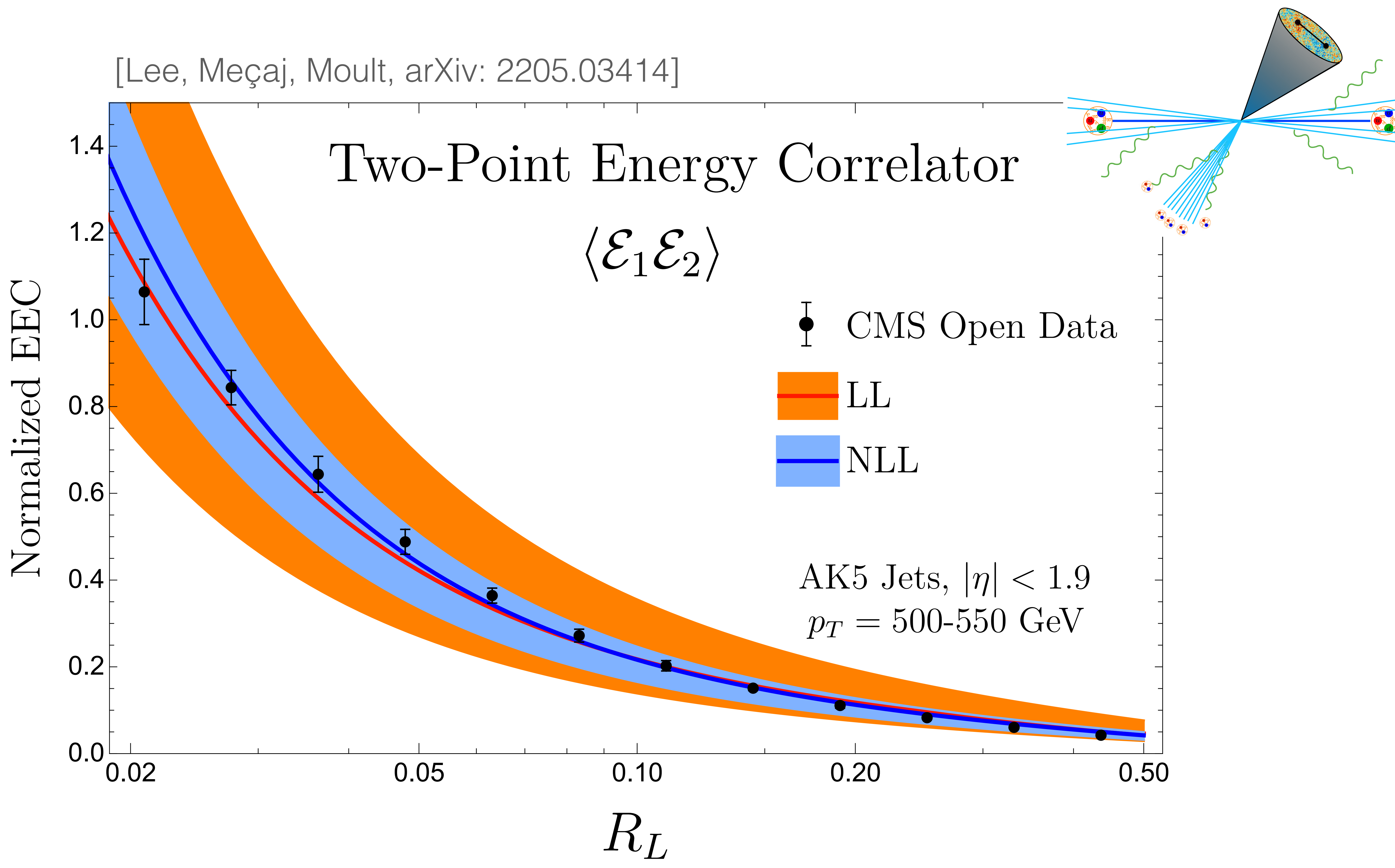
Other resummed observables at the LHC

[Rottoli, Torrielli, Vicini, arXiv: 2301.04059]



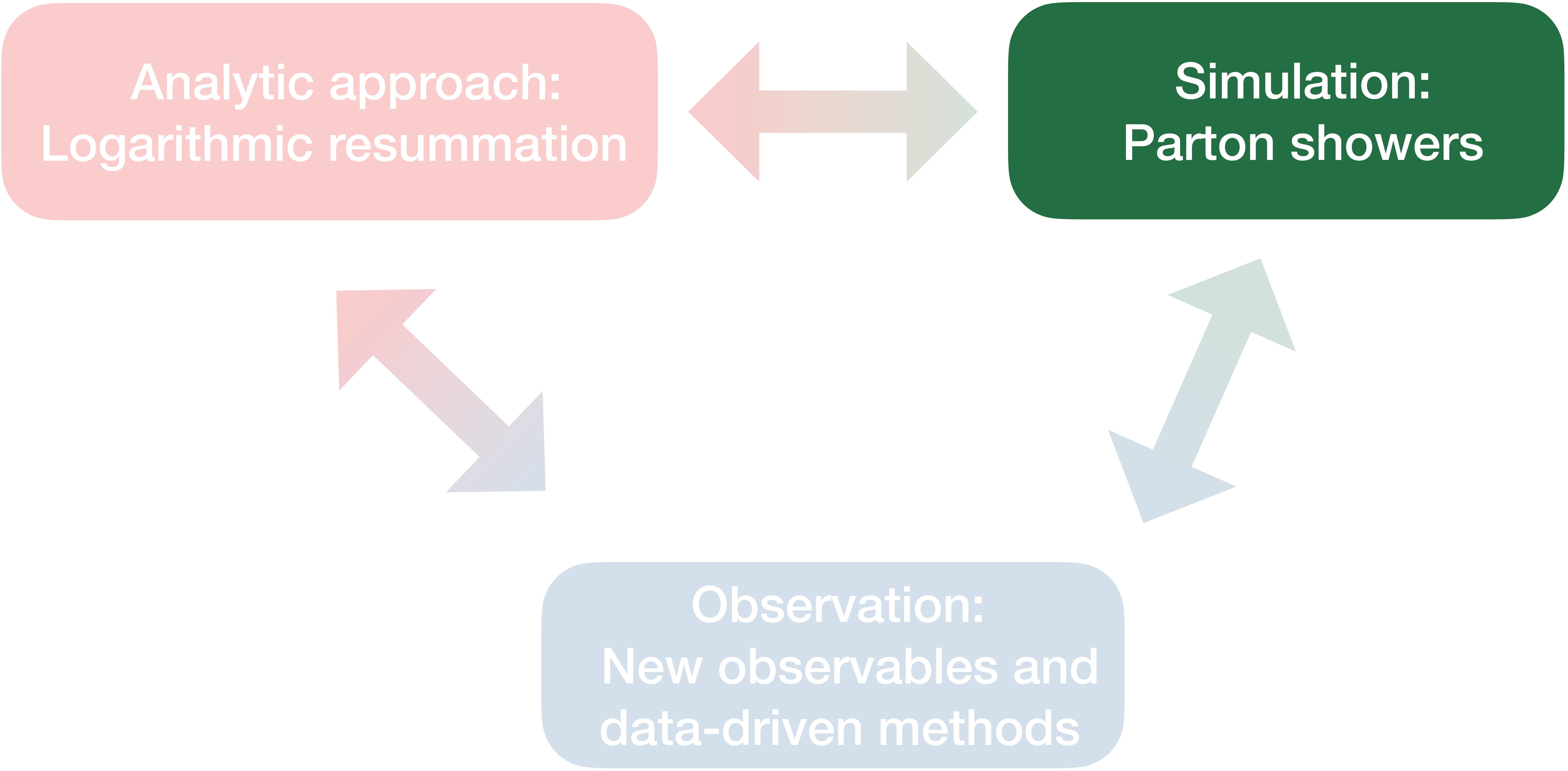
Charged lepton p_t in Drell-Yan

[Lee, Meçaj, Moult, arXiv: 2205.03414]

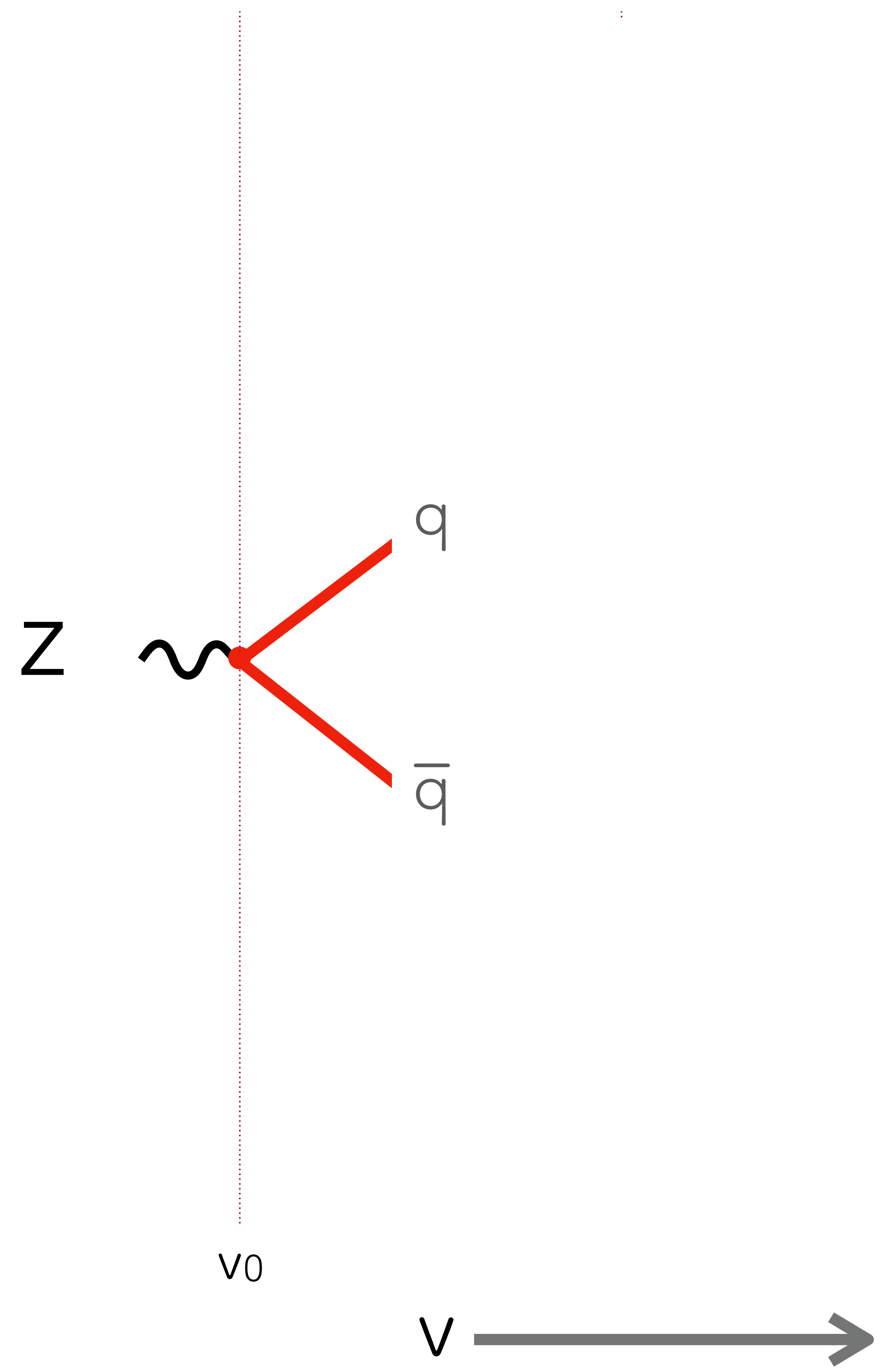


One tool to resum them all? Parton shower

Outline of this talk



QCD shower: an evolution equation



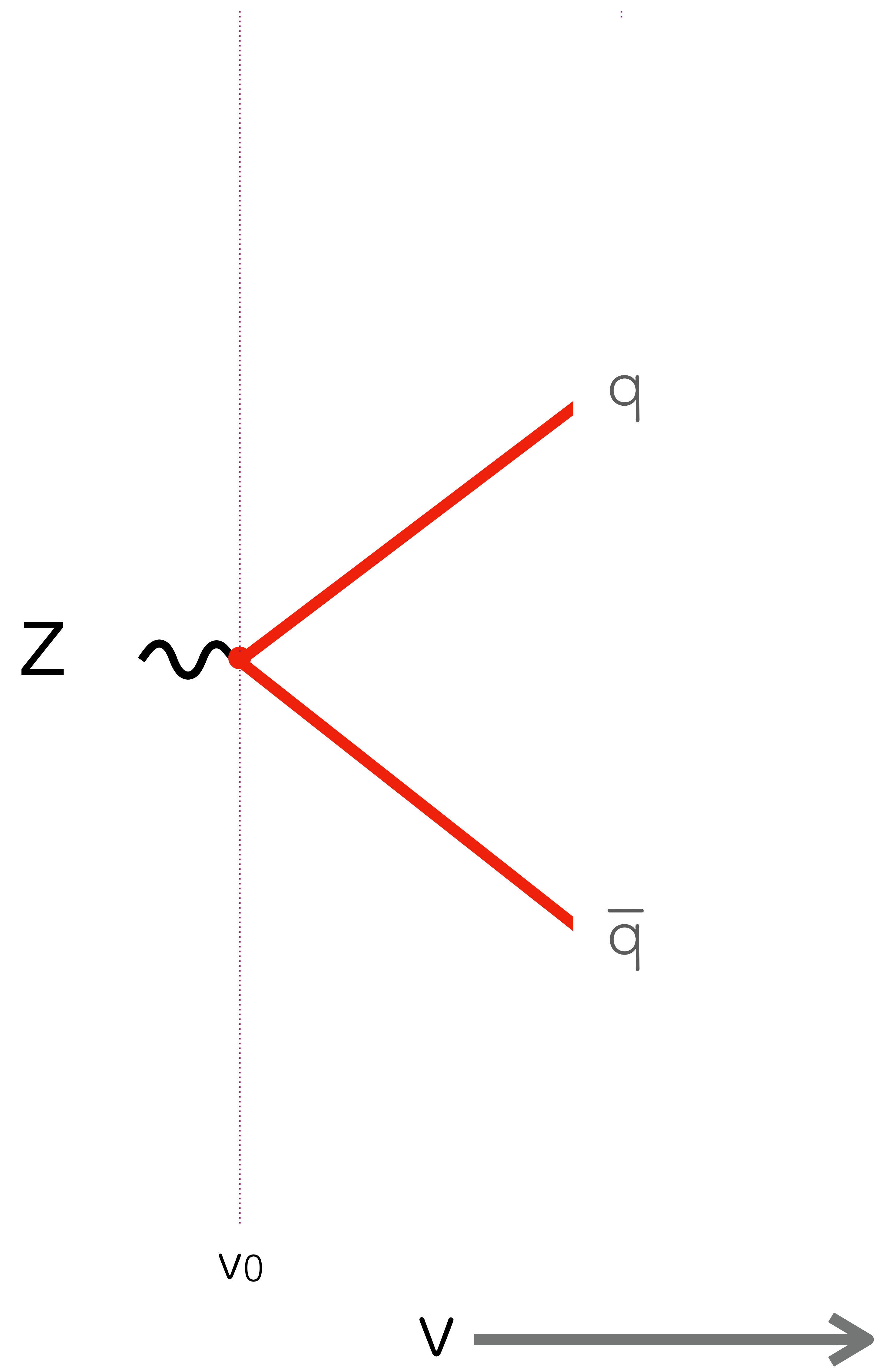
Start with $q\bar{q}$ state.

Throw a random number to determine down to what scale, v, state persists unchanged

$$\frac{\mathrm{d}P_2(v)}{\mathrm{d}v} = -f_{2\to 3}^{q\bar{q}}(v)\,P_2(v)$$

- Evolution variable: $v = k_t, \theta, t_f$

QCD shower: an evolution equation



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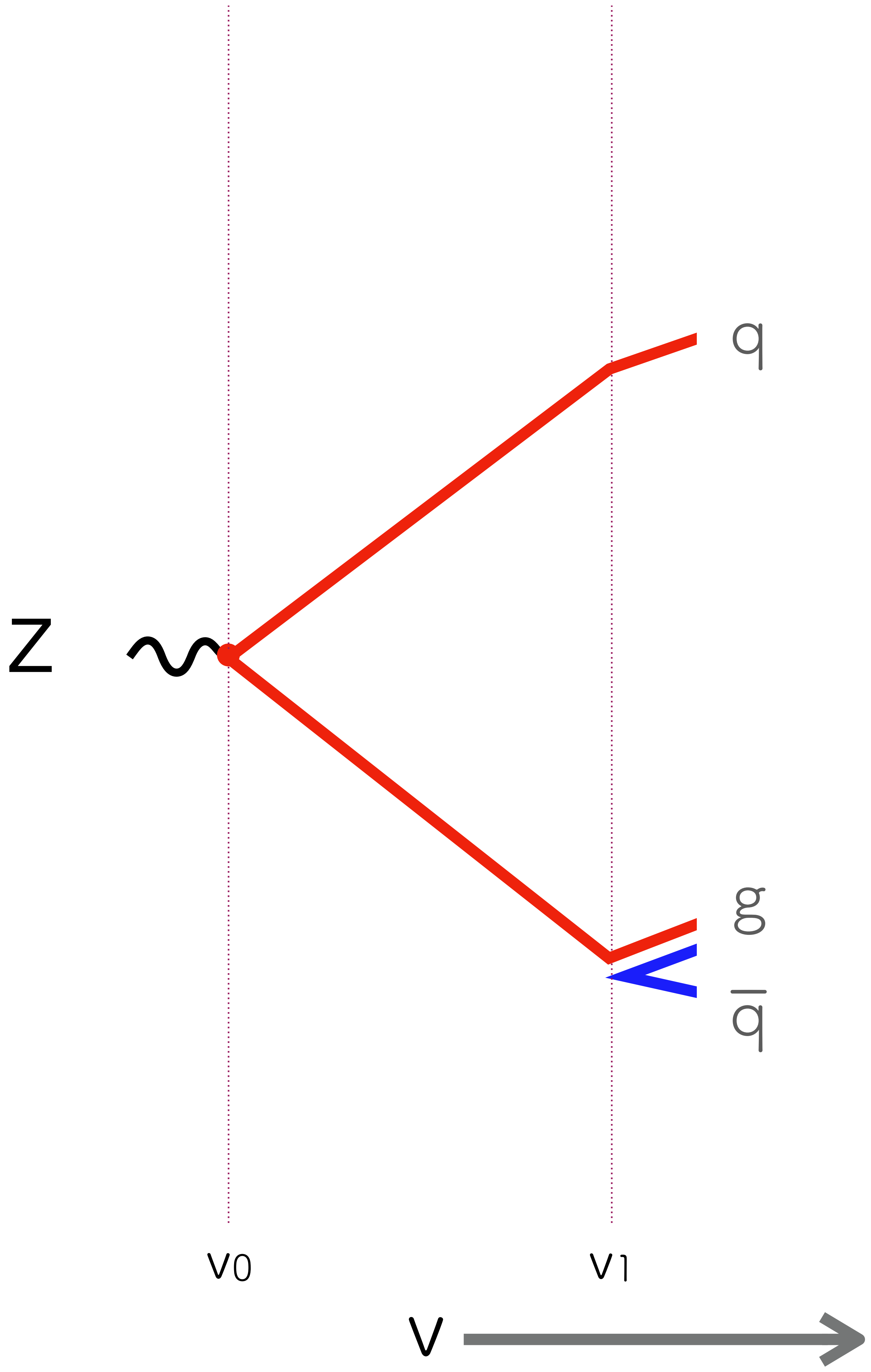
QCD shower: an evolution equation

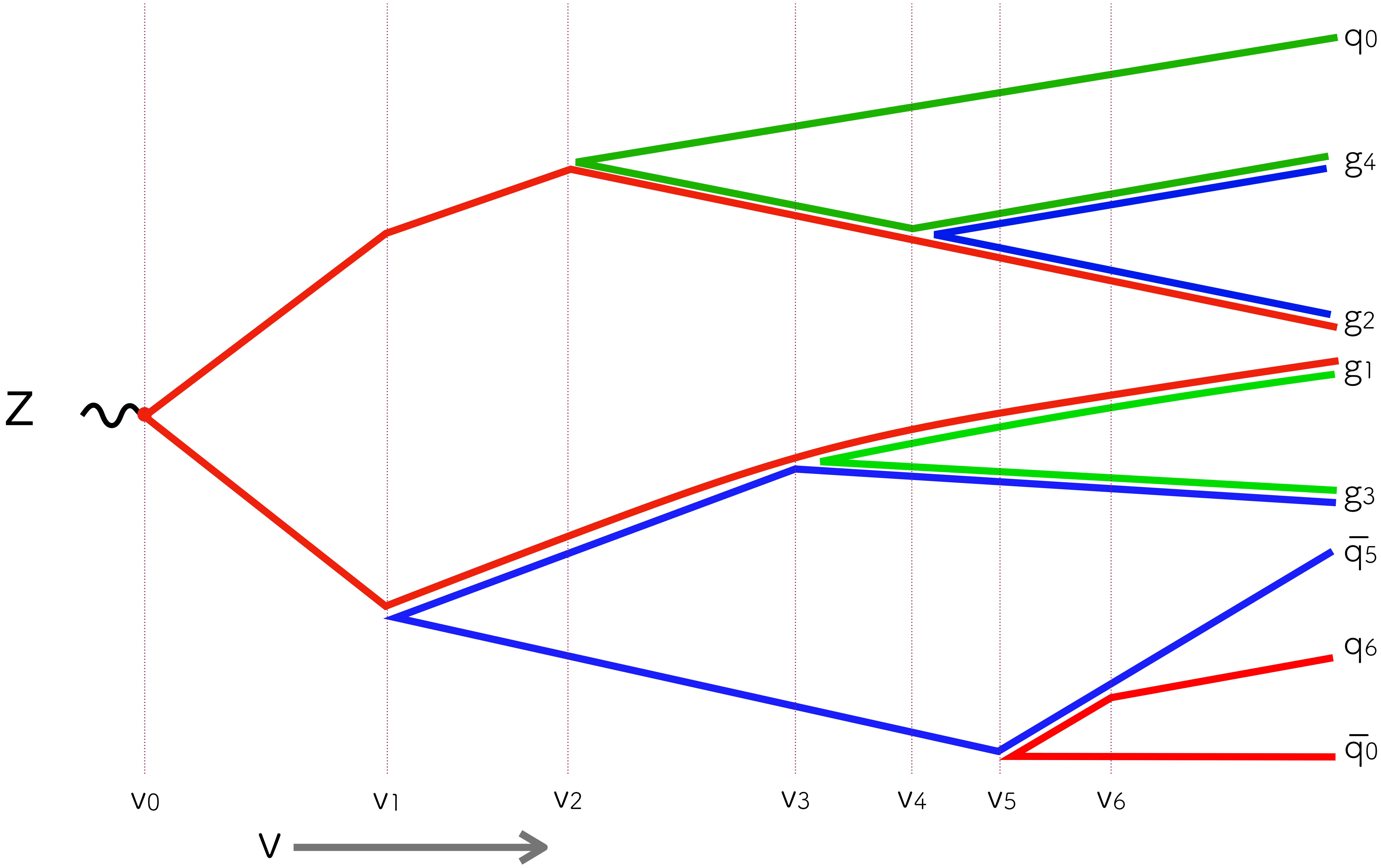


At some point, state splits (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{\mathrm{d}P_3(v)}{\mathrm{d}v} = -\left[f^{qg}_{2\to3}(v) + f^{g\bar{q}}_{2\to3}(v)\right] P_3(v)$$

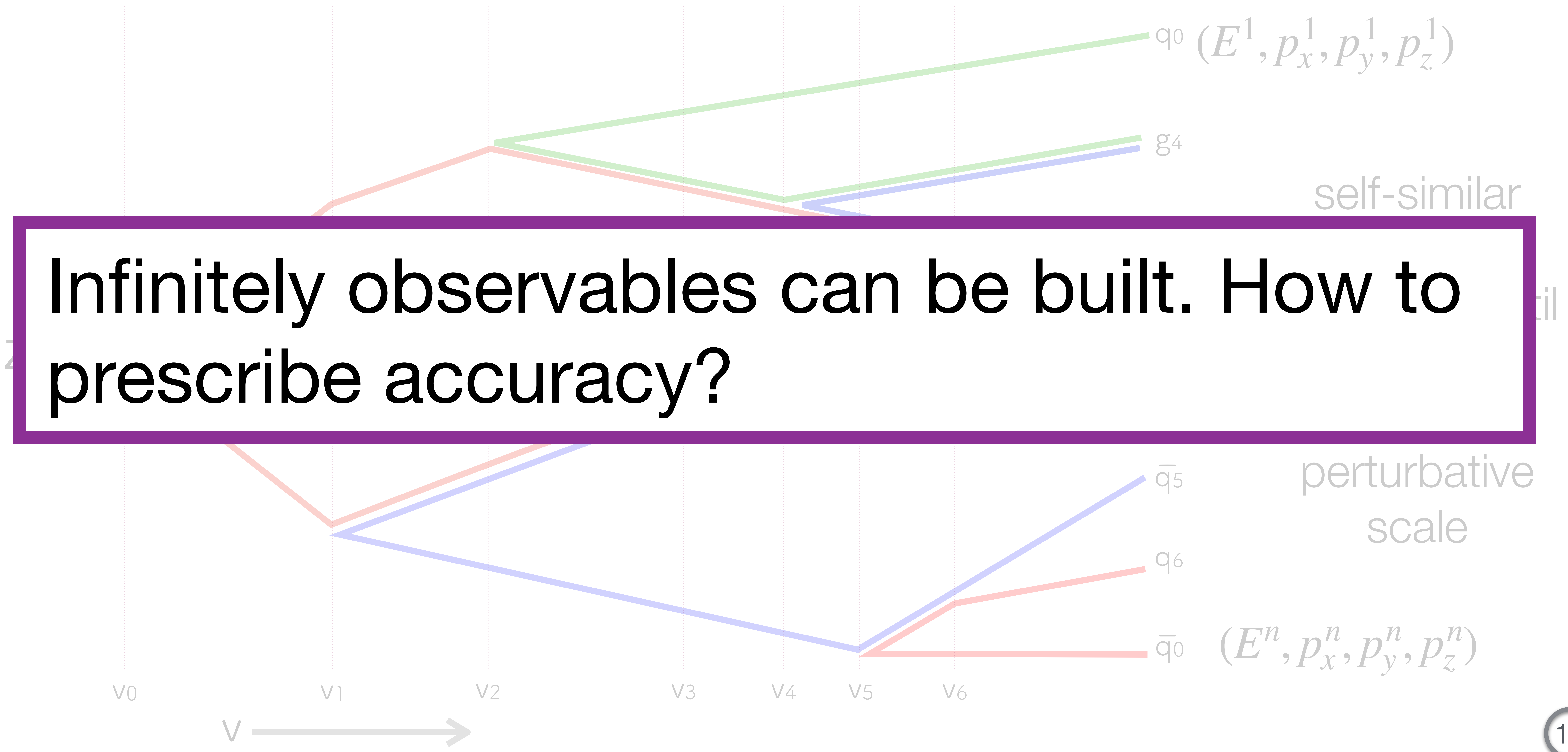
- Recoil scheme: $\tilde{p}_{q,\bar{q}} \to p_{q,\bar{q},g}$

QCD shower: an evolution equation



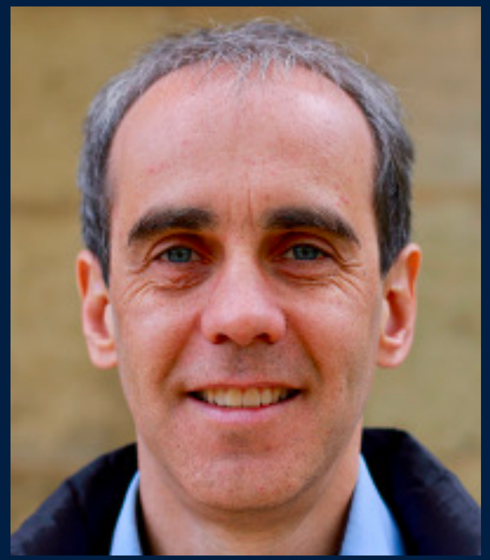
self-similar evolution continues until it reaches a non-perturbative scale

QCD shower: an evolution equation



Infinitely observables can be built. How to prescribe accuracy?

Oxford


Gavin Salam


Melissa van Beekveld


Rok Medves


Frederic Dreyer


Ludo Scyboz


Jack Helliwell

CERN


Mrinal Dasgupta


Gregory Soyez


Pier Monni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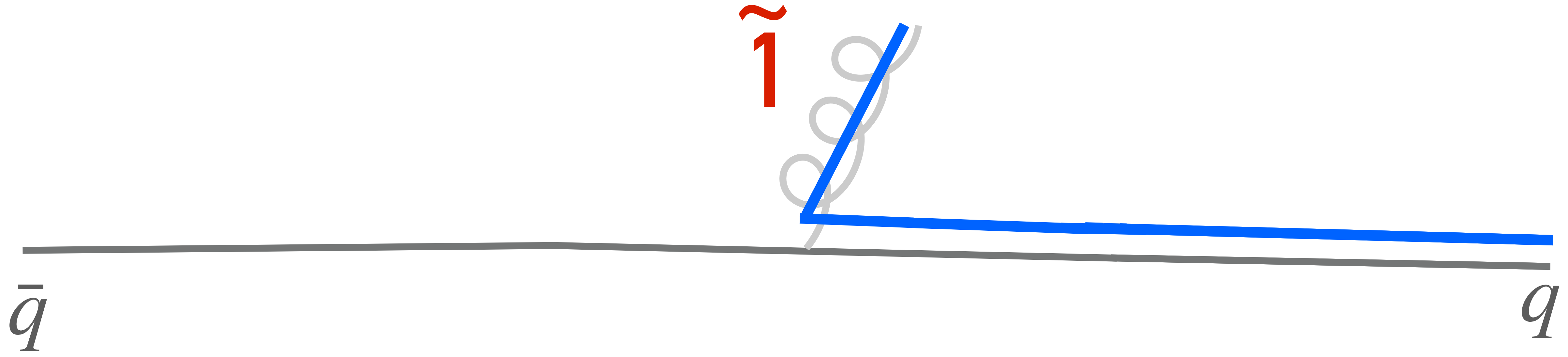
PanScales

A project to bring logarithmic understanding and accuracy to parton showers

PanScales criteria for testing log accuracy of parton showers

[Dasgupta et al. JHEP 09 (2018) 033] [Dasgupta et al. PRL 125 (2020) 5, 052002]

1 **Fixed-order:** the shower must reproduce the exact matrix element in suitable limits.



$$\mathrm{d}P_{q\to qg} \propto \frac{\alpha_s(k_t)C_F}{2\pi}\frac{\mathrm{d}k_{t1}^2}{k_{t1}^2}\frac{\mathrm{d}\theta}{\theta}$$

DL matrix element

Pre-branching components are denoted by ~

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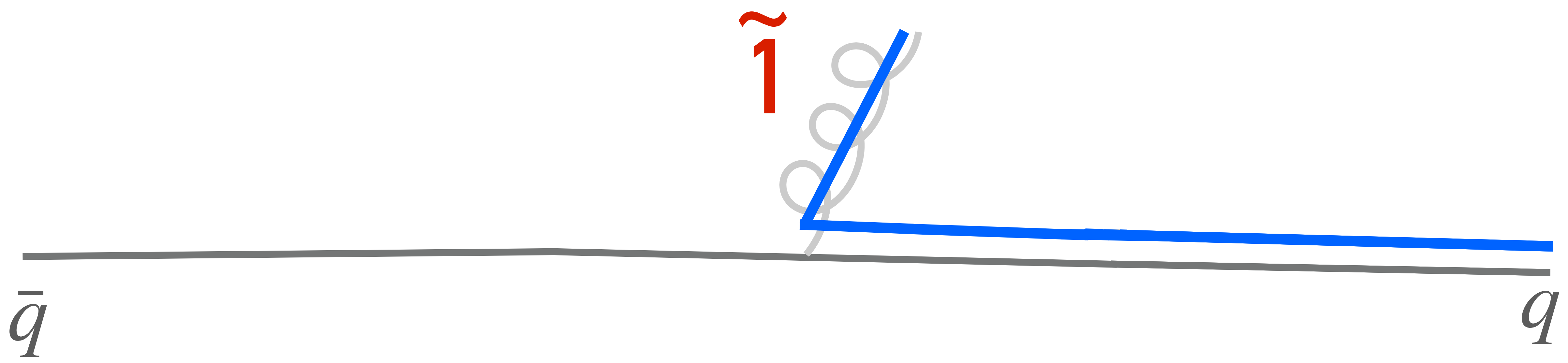

$$dP_{q\to qg} \propto \frac{\alpha_s(k_t) C_F}{2\pi} \frac{dk_{t1}^2}{k_{t1}^2} \frac{d\theta}{\theta}$$

e.g. correct matrix element for two well-separated emissions

$$dP_{q\to qgg} \propto \left(\frac{\alpha_s C_F}{2\pi}\right)^2 \frac{dk_{t1}^2}{k_{t1}^2} \frac{d\theta}{\theta} \times \frac{dk_{t2}^2}{k_{t2}^2} \frac{d\theta_2}{\theta_2}$$

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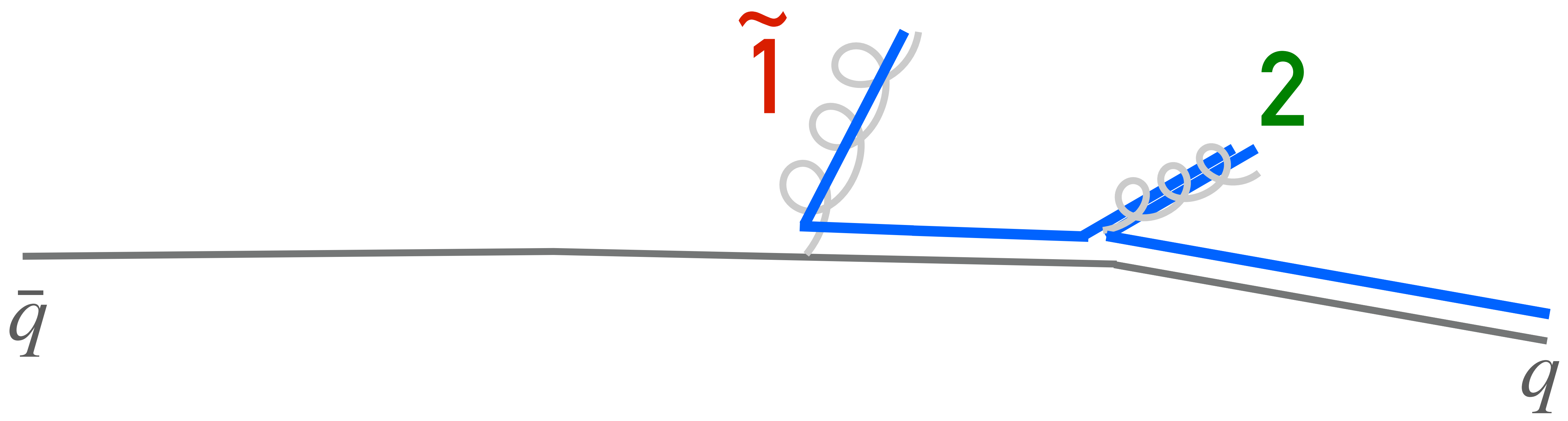


Only achieved if emission of 2 takes transverse recoil from q

$$k_{t1} = \tilde{k}_{t1}$$

$$\mathrm{d}P_{q\to qgg} \propto \left(\frac{\alpha_s C_F}{2\pi}\right)^2 \frac{\mathrm{d}k_{t1}^2}{k_{t1}^2}\frac{\mathrm{d}\theta}{\theta} \times \frac{\mathrm{d}k_{t2}^2}{k_{t2}^2}\frac{\mathrm{d}\theta_2}{\theta_2}$$

PanScales criteria for testing log accuracy of parton showers

[Dasgupta et al. JHEP 09 (2018) 033] [Dasgupta et al. PRL 125 (2020) 5, 052002]

1. **Fixed-order:** the shower must reproduce the exact matrix element in suitable limits.

2. **All-orders:** the shower must reproduce analytic resummation results for a broad range of observables such as
   - Global event shapes
   - Non-global observables
   - Fragmentation functions
   - Multiplicities (our calculation can be used for NNLL showers)

PanScales criteria for testing log accuracy of parton showers

[Dasgupta et al. JHEP 09 (2018) 033] [Dasgupta et al. PRL 125 (2020) 5, 052002]

1 **Fixed-order:** the shower must reproduce the exact matrix element in suitable limits.

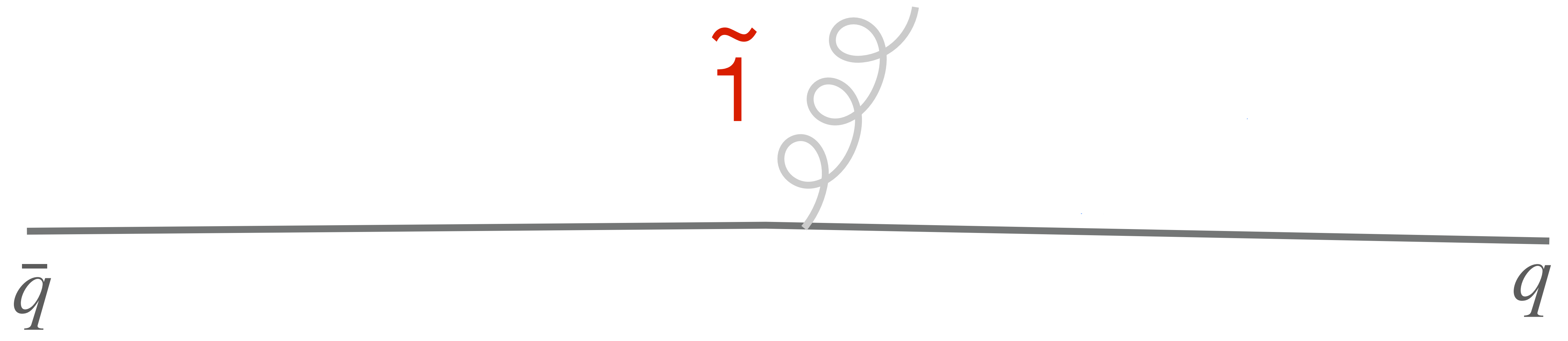
Analytic approach: Logarithmic resummation ⟷ **Simulation: Parton showers**

... ust r... produc... an... for a broad range of observables

- Global event shapes
- Non-global observables
- Fragmentation functions
- Multiplicities (our calculation can be used for NNLL showers)

Key problem of standard dipole showers

Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



Shower generates $\mathrm{d}P_{\mathrm{DL}} \propto \frac{\alpha_s(k_t) C_F}{2\pi} \frac{\mathrm{d}k_t^2}{k_t^2} \frac{\mathrm{d}\theta}{\theta}$

Pre-branching components are denoted by ~

Key problem of standard dipole showers

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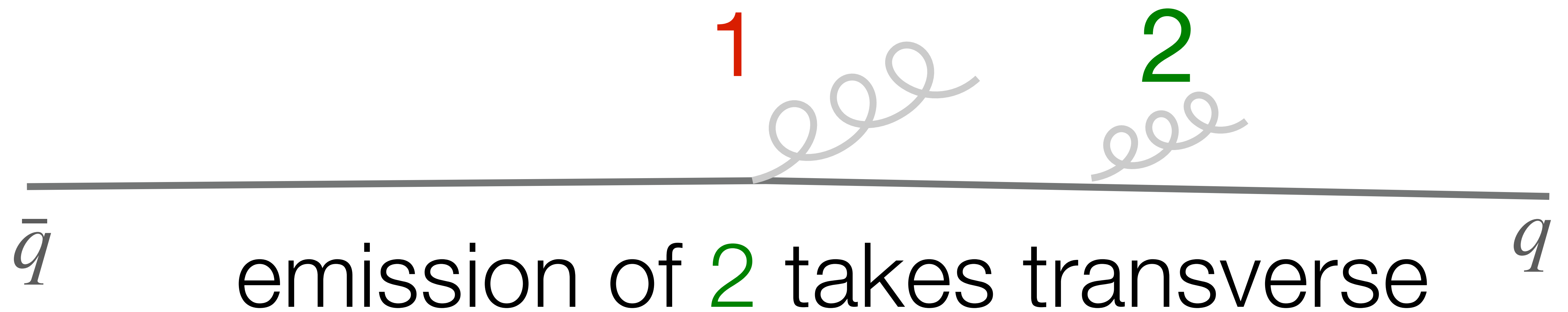


emission of 2 takes transverse recoil from 1

$$\Downarrow$$

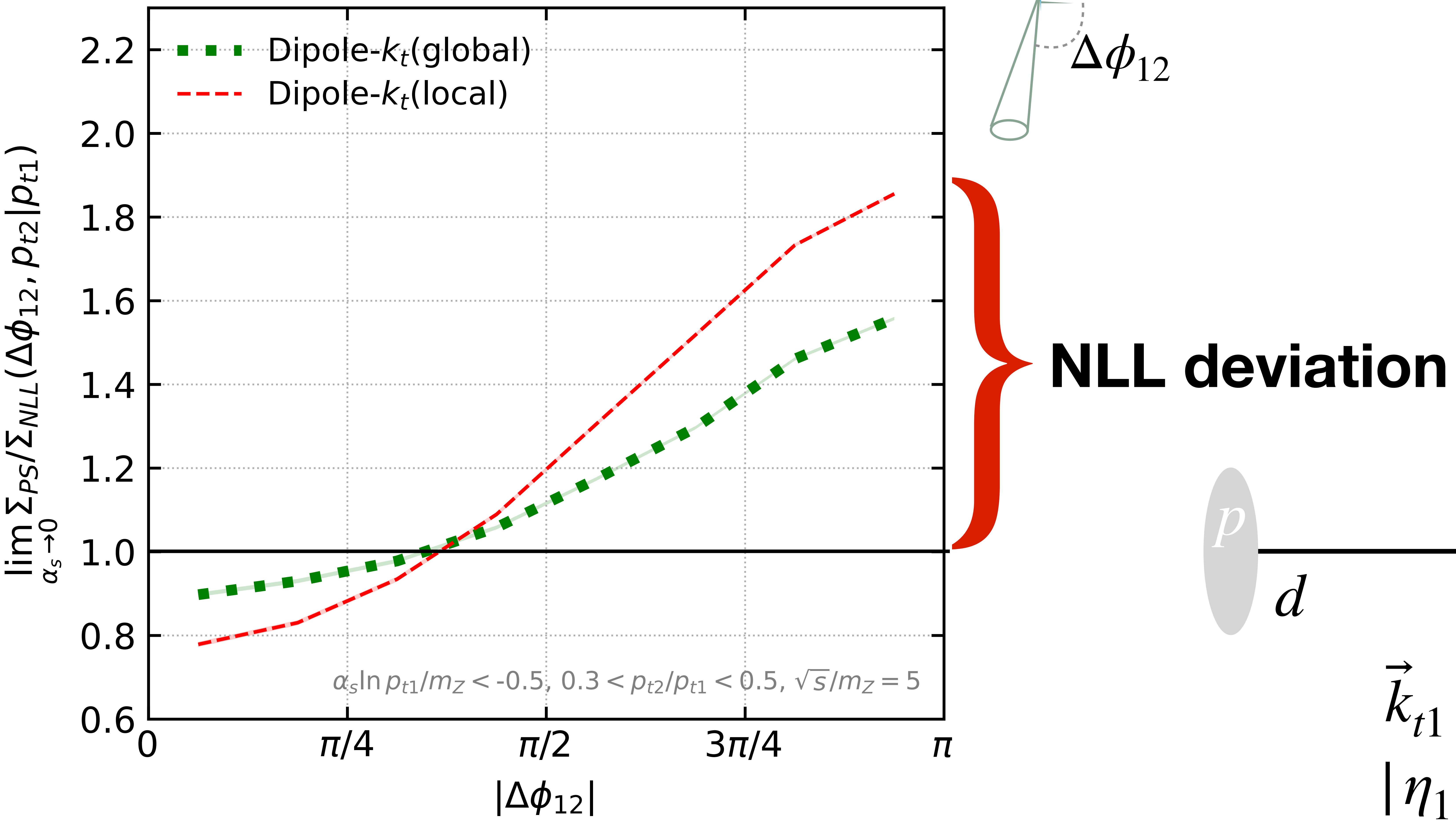
$$k_{t1} \neq \tilde{k}_{t1}$$

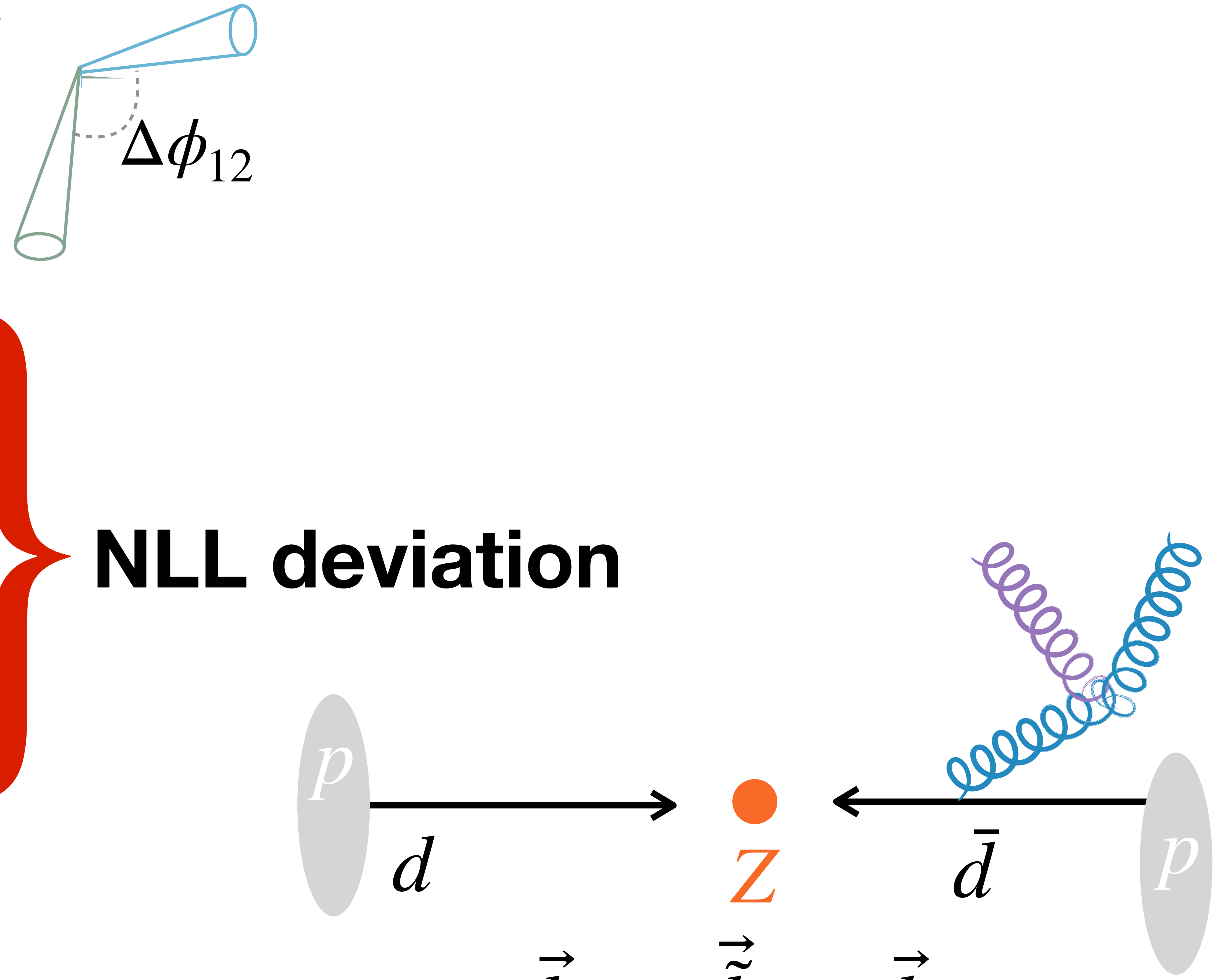
Wrong matrix element after ensuring energy-momentum conservation

Testing the accuracy of standard dipole showers: $pp \to Z$

[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]

Azimuthal angle between leading jets





$$\vec{k}_{t1} = \vec{\tilde{k}}_{t1} - \vec{k}_{t2}$$

$$|\eta_1 - \eta_2| \gg 1$$

Wrong recoil scheme translates into all-orders failure

Testing the accuracy of standard dipole showers: $pp \to Z$

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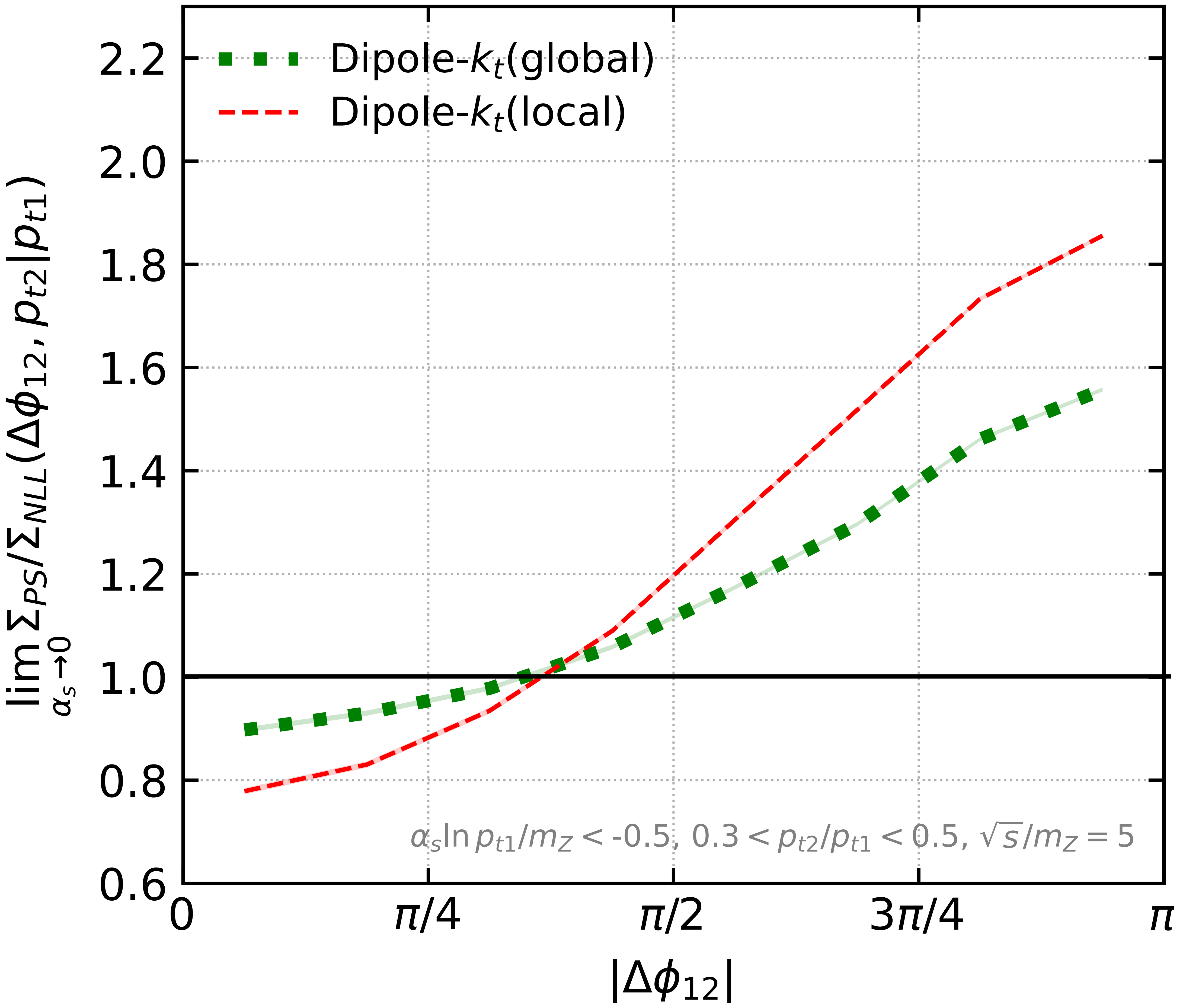
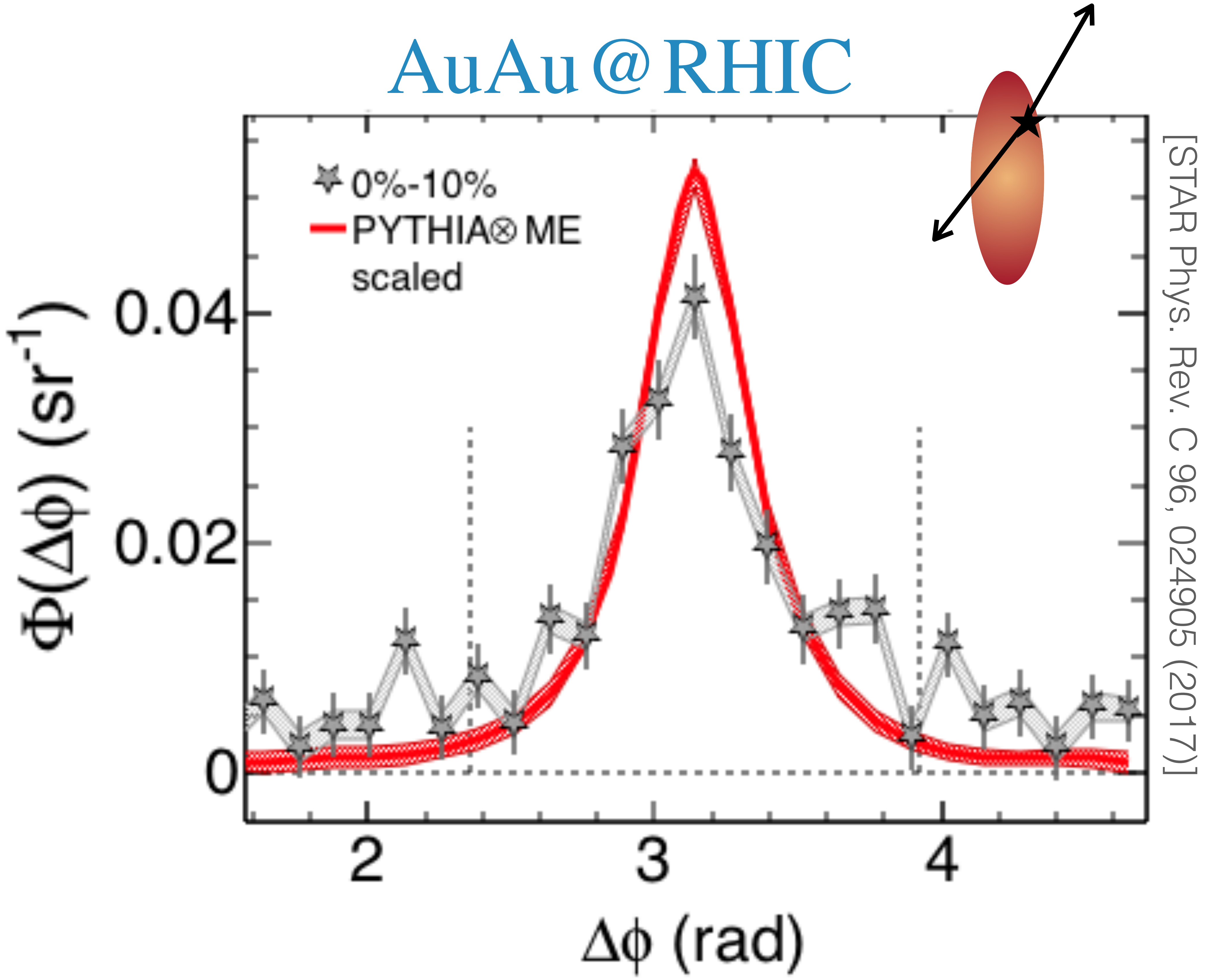


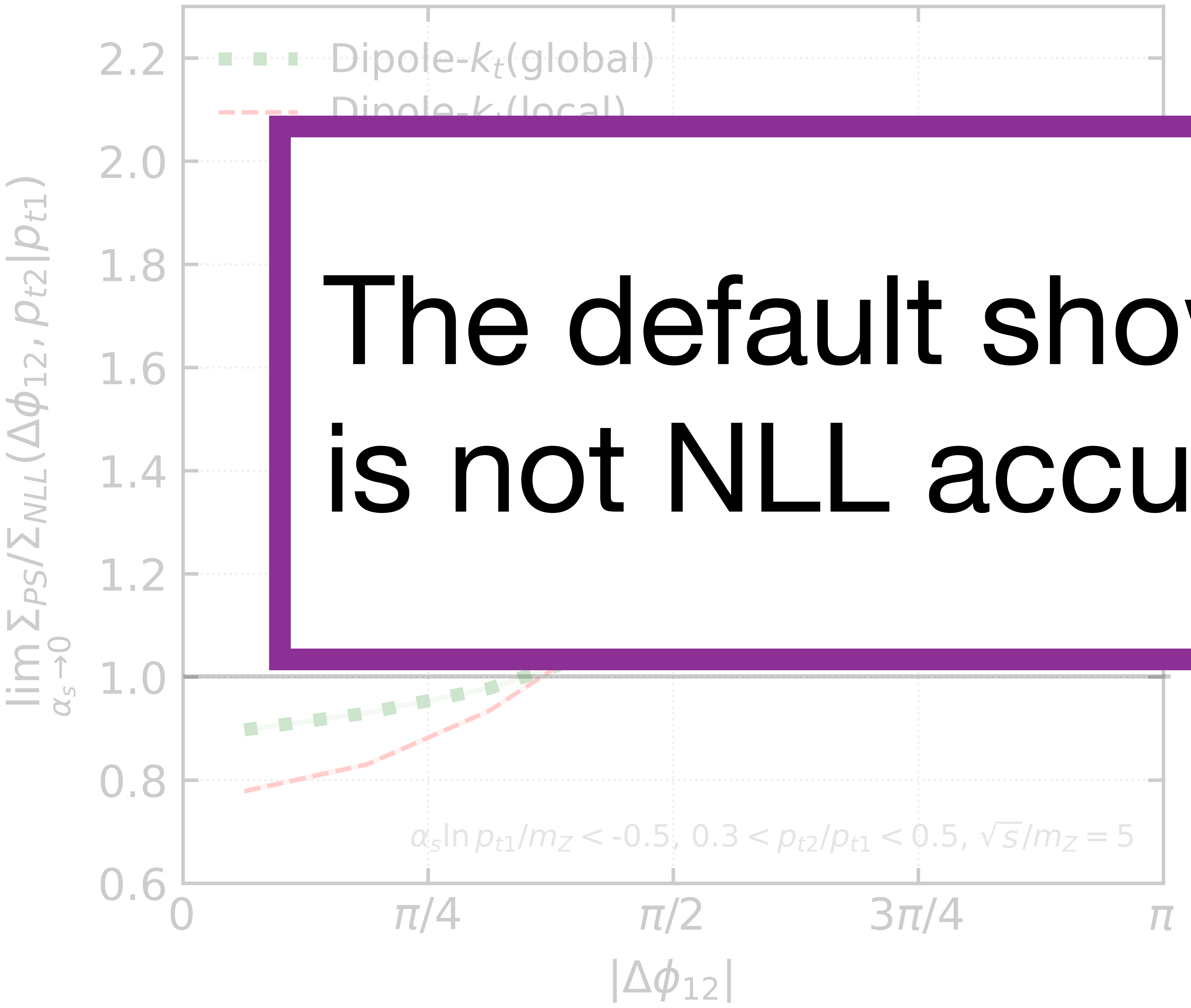
~

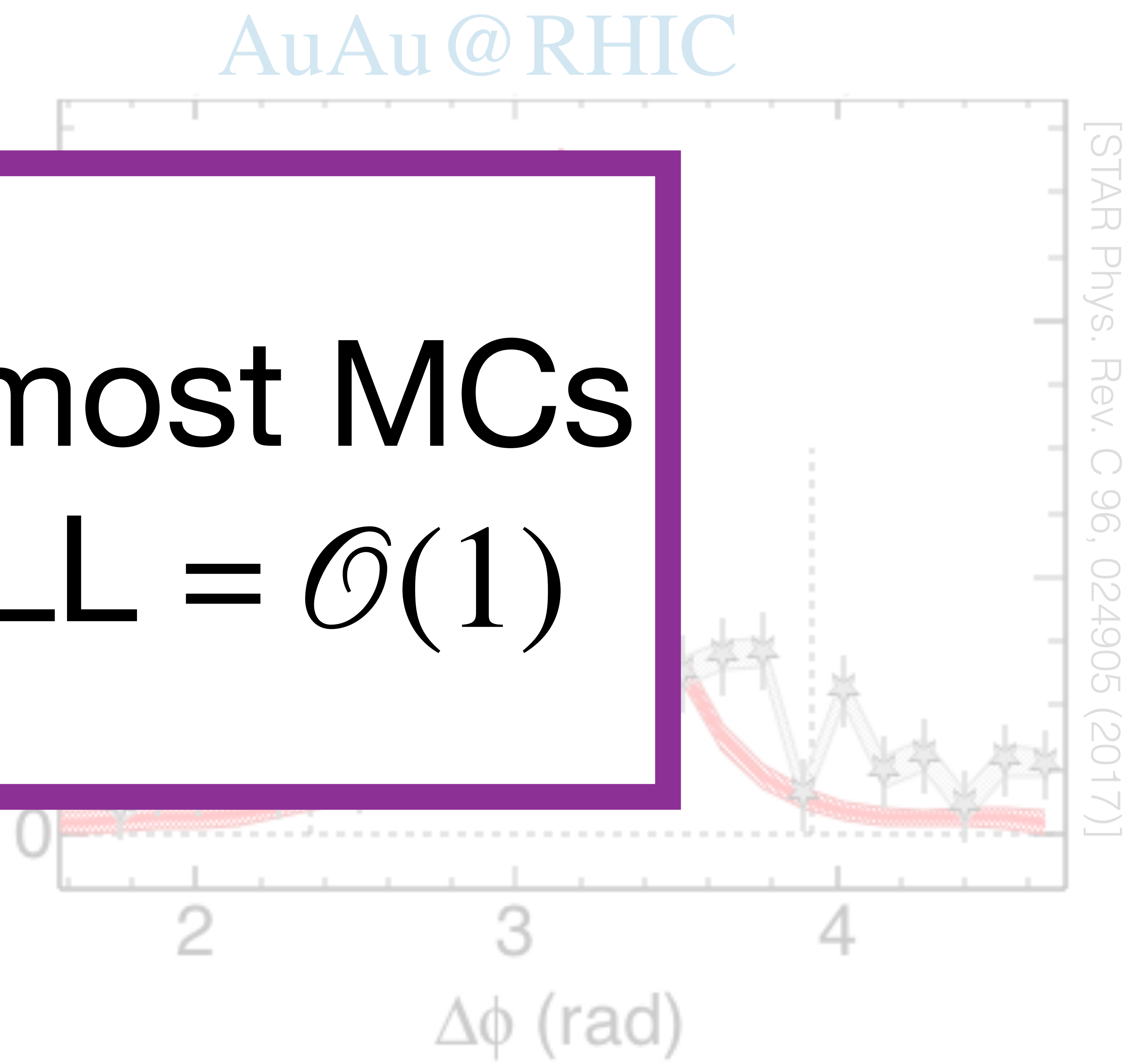


Azimuthal correlations play a major role in heavy-ion physics

Testing the accuracy of standard dipole showers: $pp \to Z$

Azimuthal angle between leading jets



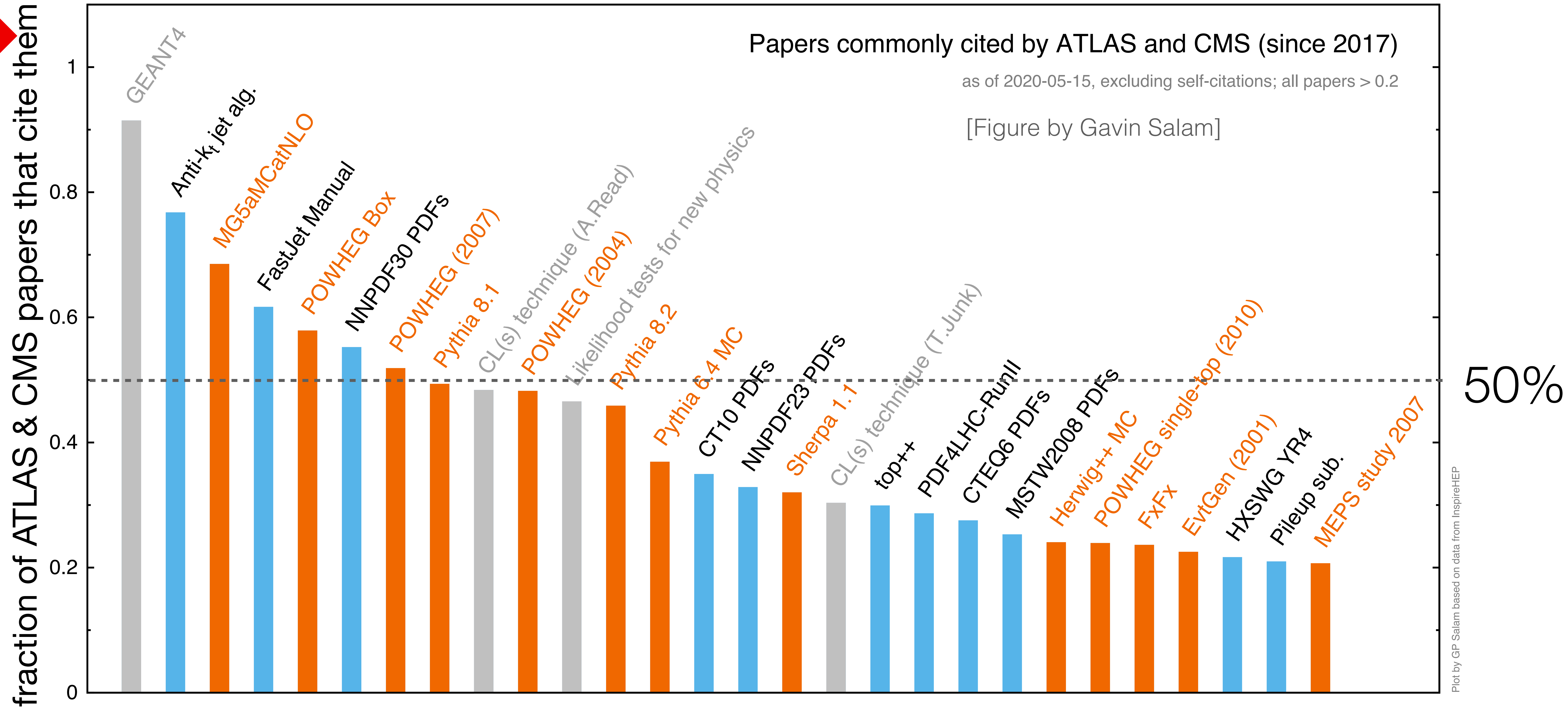


The default shower in most MCs is not NLL accurate. NLL $= \mathcal{O}(1)$

Azimuthal correlations play a major role in heavy-ion physics

Motivations to push for higher accuracy

1



MC generators are ubiquitous in LHC analyses

Motivations to push for higher accuracy

2 Extraction of fundamental parameters of the Standard model

$$m_W = 80363 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

[LHCb JHEP 01 (2022) 036]

17_{theory} ← 11 MeV due to MC modelling

$$m_{\text{top}} = 174.41 \pm 0.39_{\text{stat}} \pm 0.66_{\text{syst.}} \pm 0.25_{\text{recoil}} \text{ GeV}$$

[ATLAS 2209.00583]

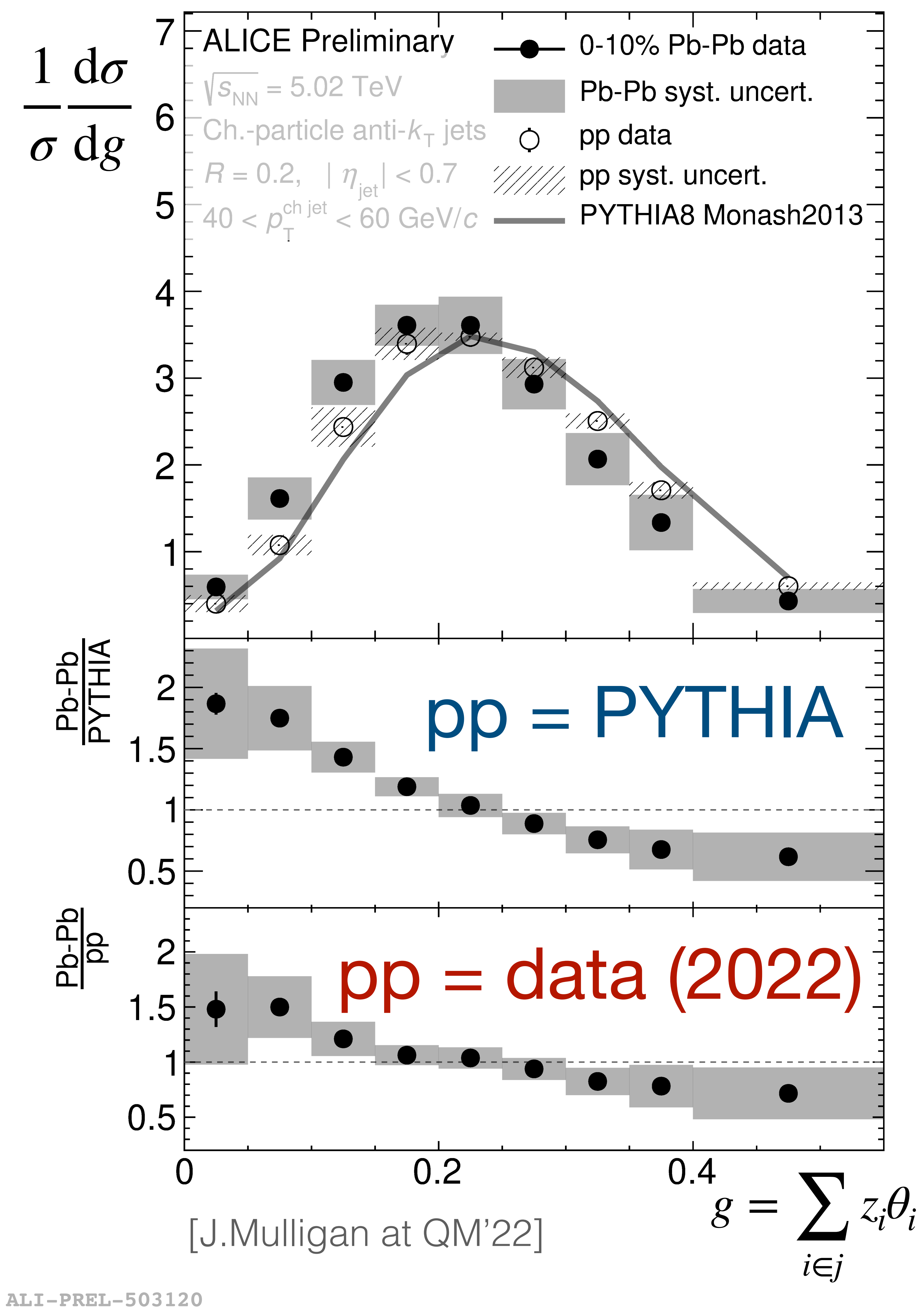
$0.66_{\text{syst.}}$ ← 0.24 GeV due to MC modelling

0.25_{recoil} ← purely shower modelling

MC discrepancies are a fundamental limit on LHC precision potential

Motivations to push for higher accuracy

3



A precise vacuum benchmark is fundamental for any interpretation of heavy-ion data.

Key aspects of NLL PanScales showers

	PanLocal	PanGlobal
• Evolution variable:	$k_t\sqrt{\theta}$	$k_t, k_t\sqrt{\theta}$
• Recoil scheme:	Local	$\perp$: global (e+e-, all event; pp, colour singlet) $+, -$: local

• Dipole partitioning: Dipole midpoint defined in the event frame

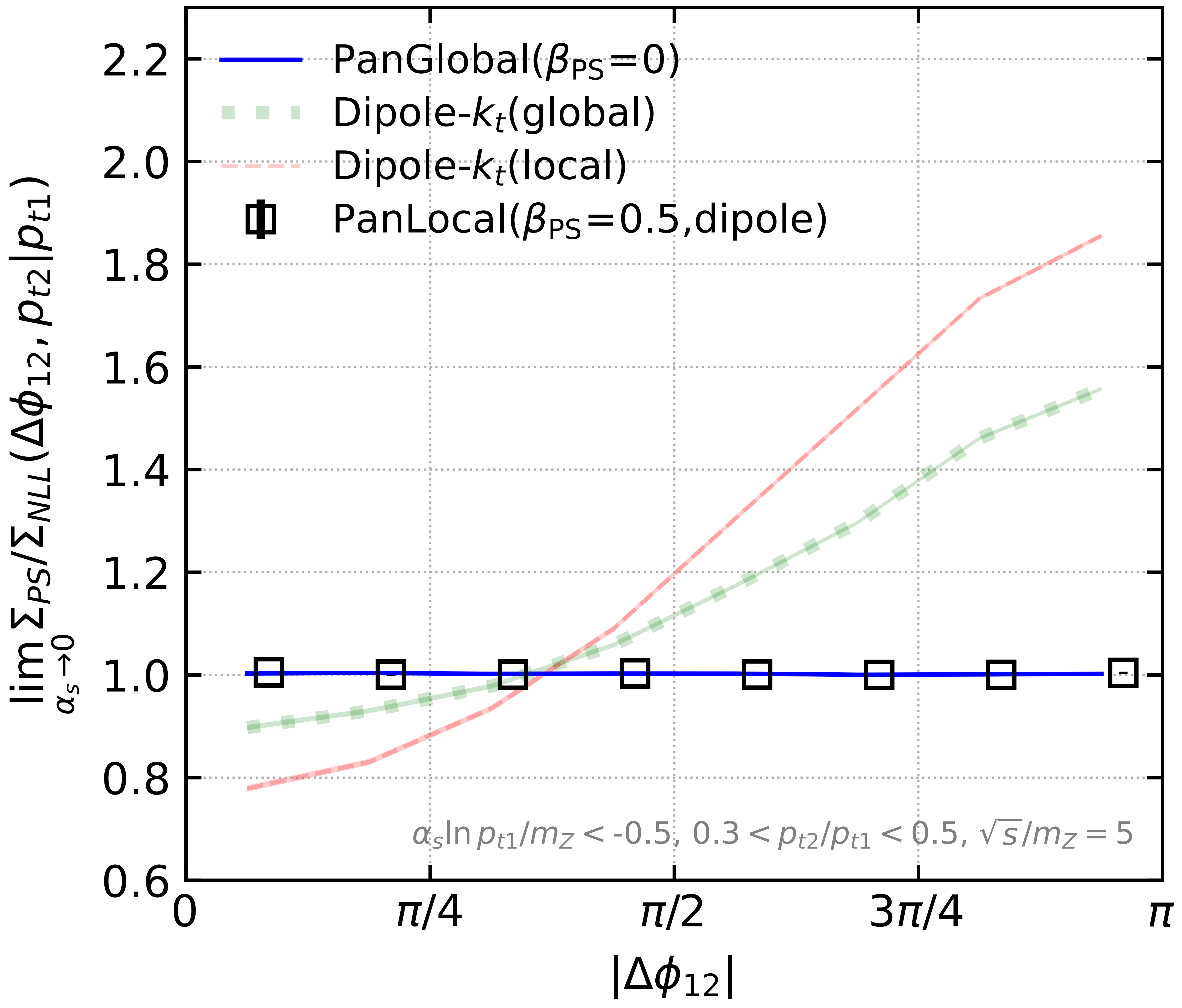
+ Spin correlations (required for NLL)

+ Subleading colour corrections ($\frac{1}{N_c^2} \sim 0.1 \sim \text{NLL}$)

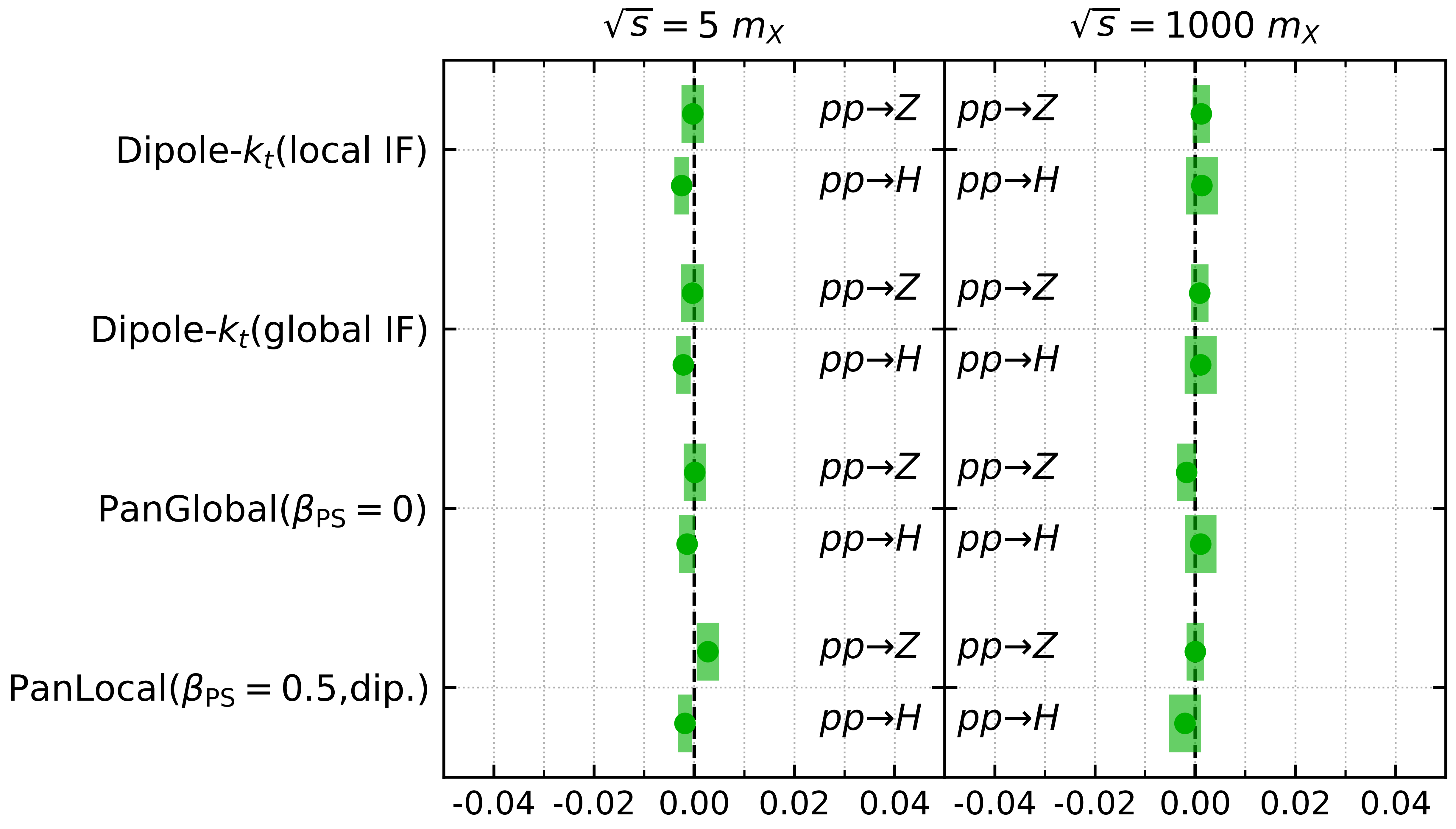
Testing the NLL accuracy of PanScales showers: $pp \to Z$

[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]

Azimuthal angle between leading jets



Subjet multiplicity

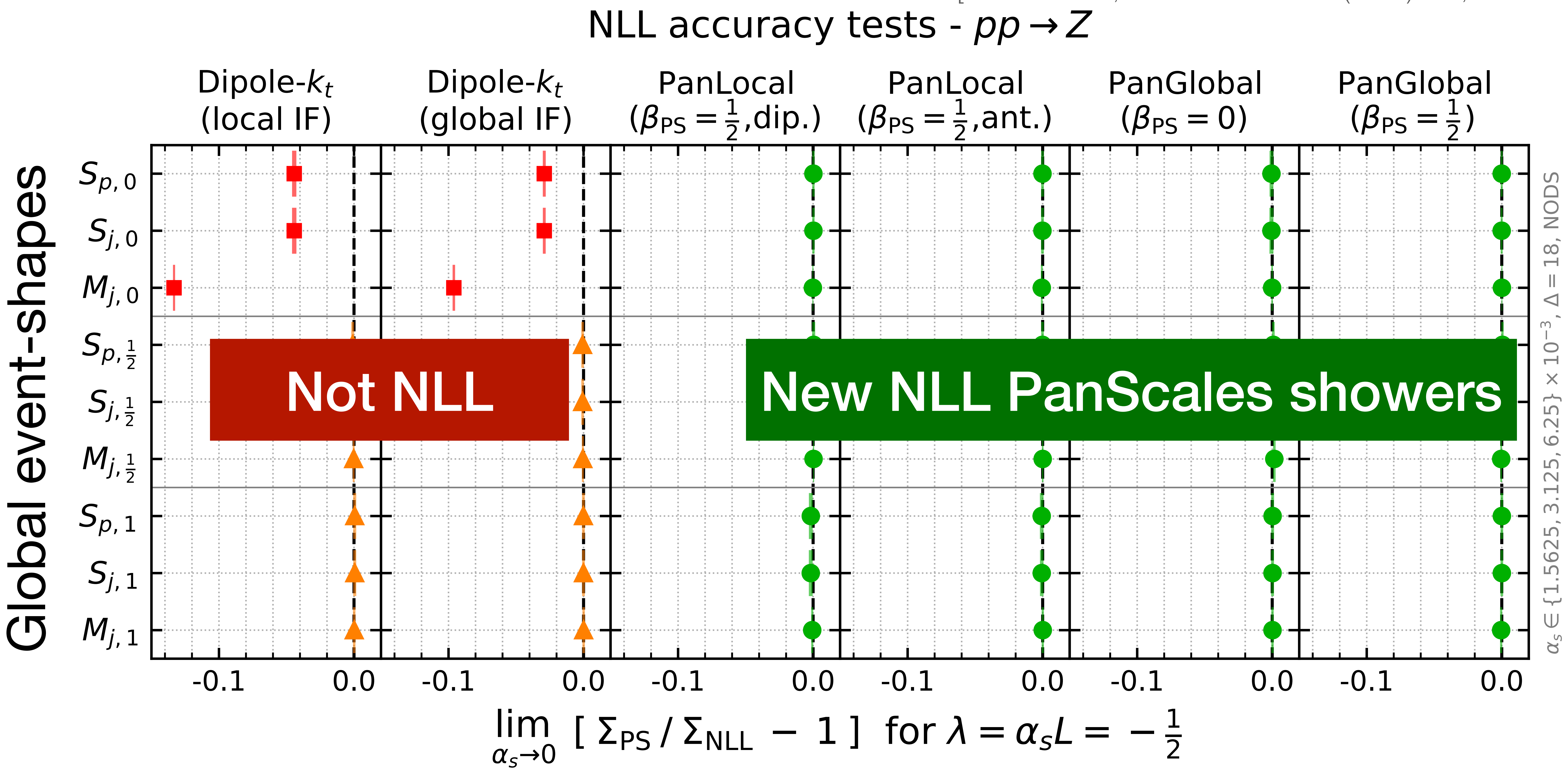


green == shower matches NDL analytics

Shower testing also pushes for higher accuracy analytic resummations

Testing the NLL accuracy of PanScales showers: $pp \to Z$

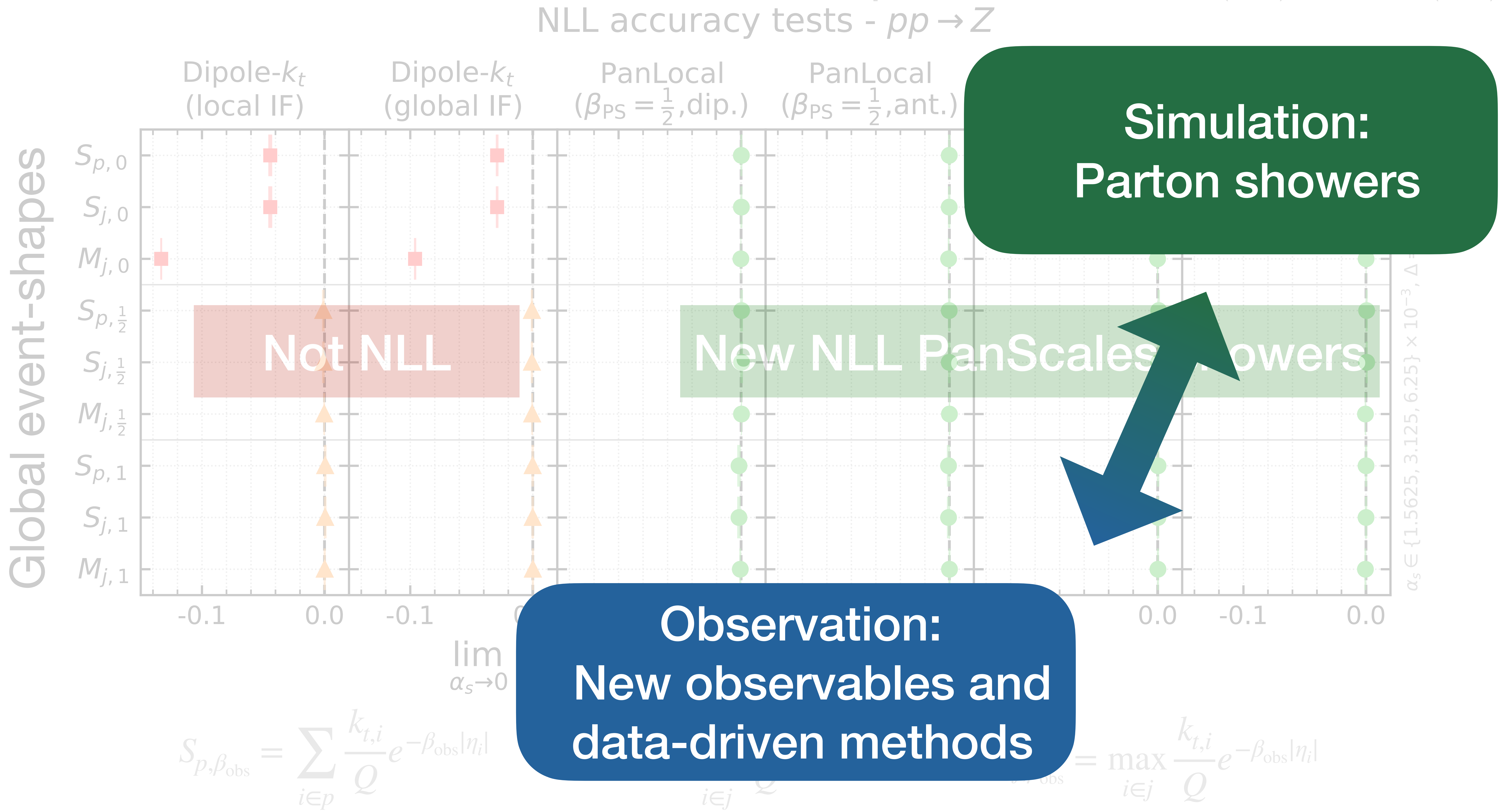
[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]



$$S_{p,\beta_{obs}} = \sum_{i \in p} \frac{k_{t,i}}{Q} e^{-\beta_{obs}|\eta_i|} \qquad S_{j,\beta_{obs}} = \sum_{i \in j} \frac{k_{t,i}}{Q} e^{-\beta_{obs}|\eta_i|} \qquad M_{j,\beta_{obs}} = \max_{i \in j} \frac{k_{t,i}}{Q} e^{-\beta_{obs}|\eta_i|}$$

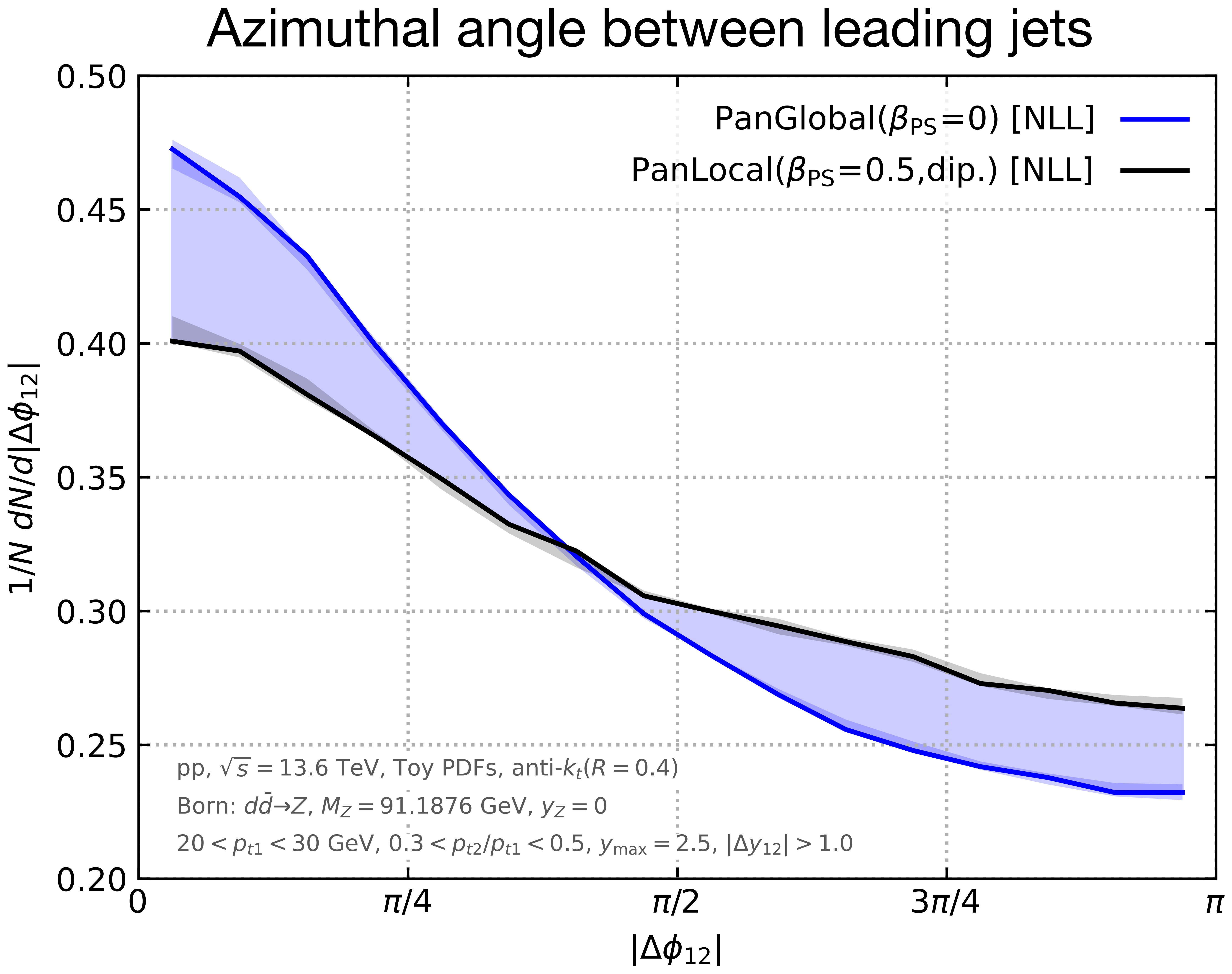
Testing the NLL accuracy of PanScales showers: $pp \to Z$

[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]



Towards phenomenology with PanScales showers

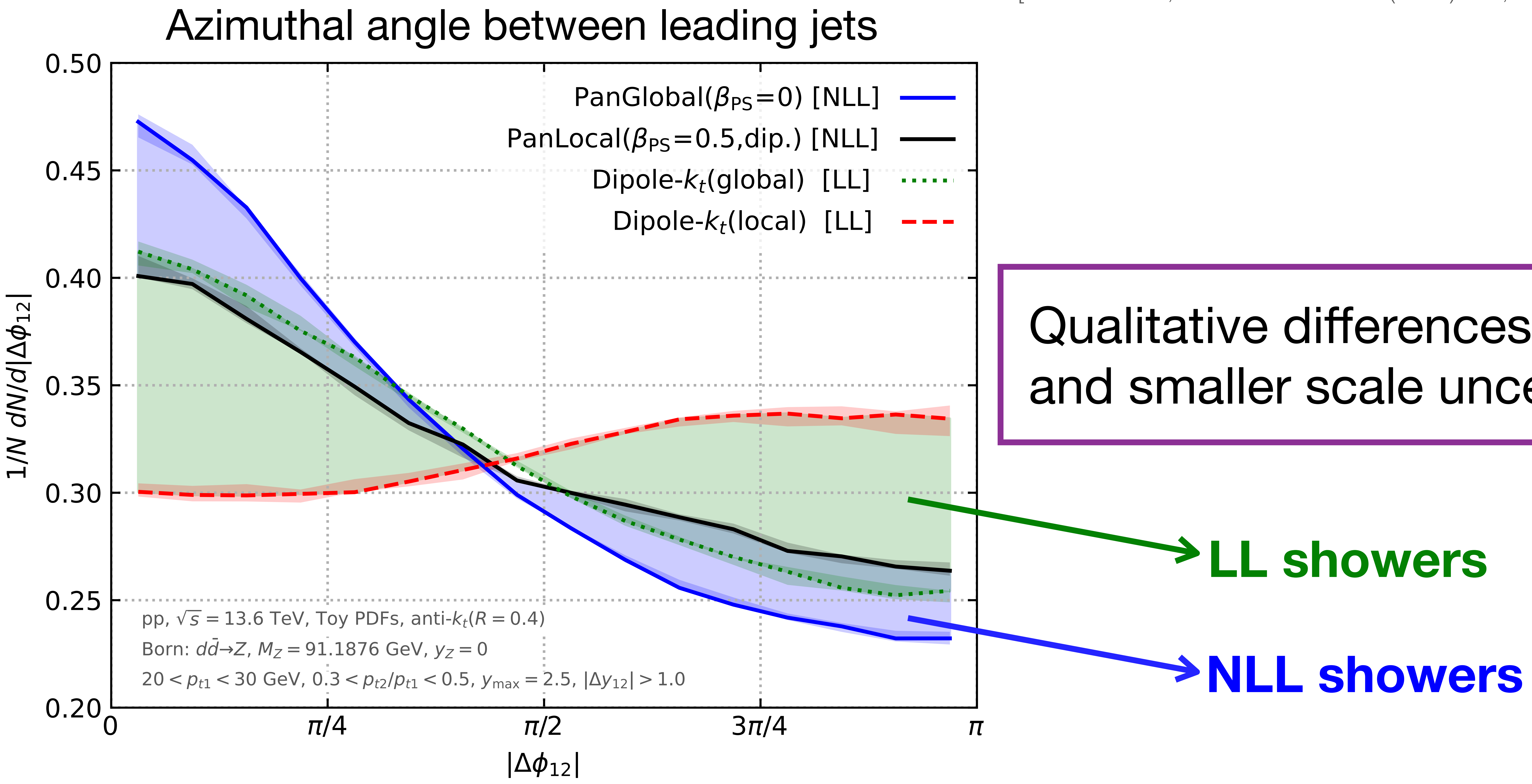
[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]



Differences among NLL showers indicate the size of higher orders.

Towards phenomenology with PanScales showers

[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]

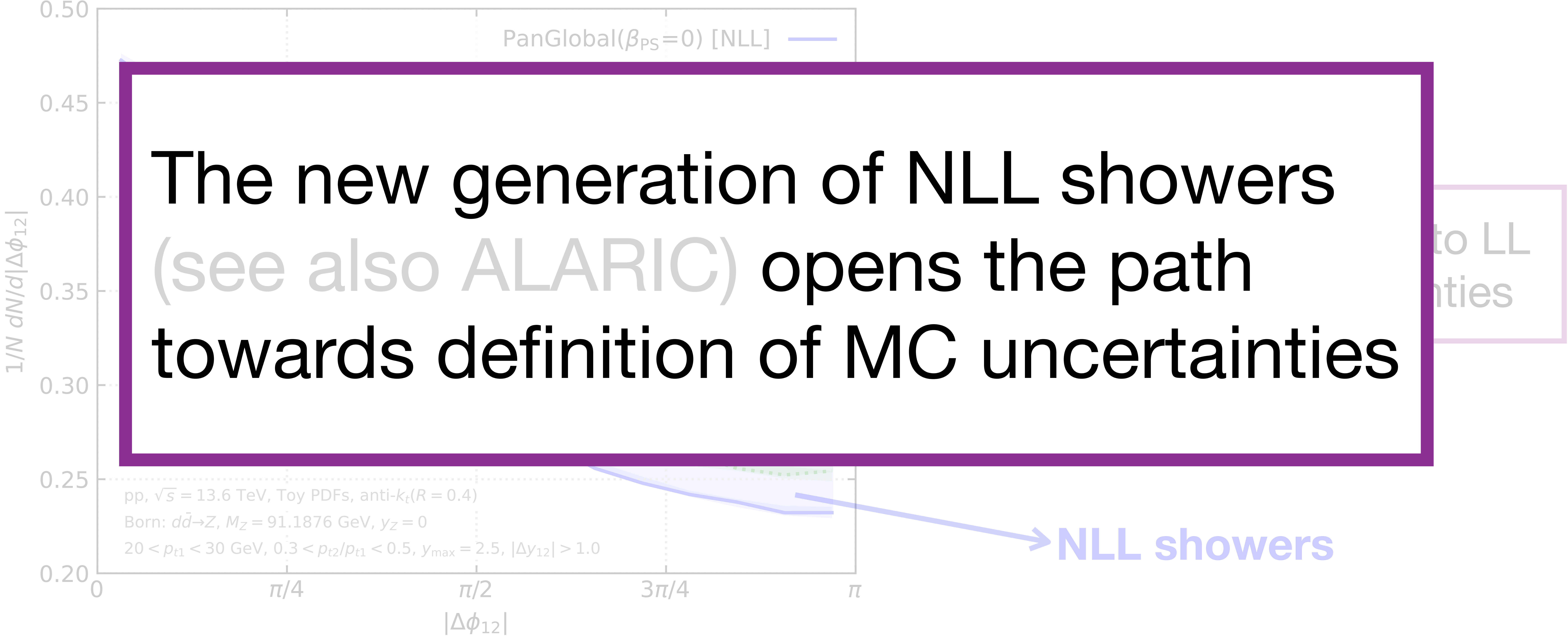


Qualitative differences wrt to LL and smaller scale uncertainties

Towards phenomenology with PanScales showers

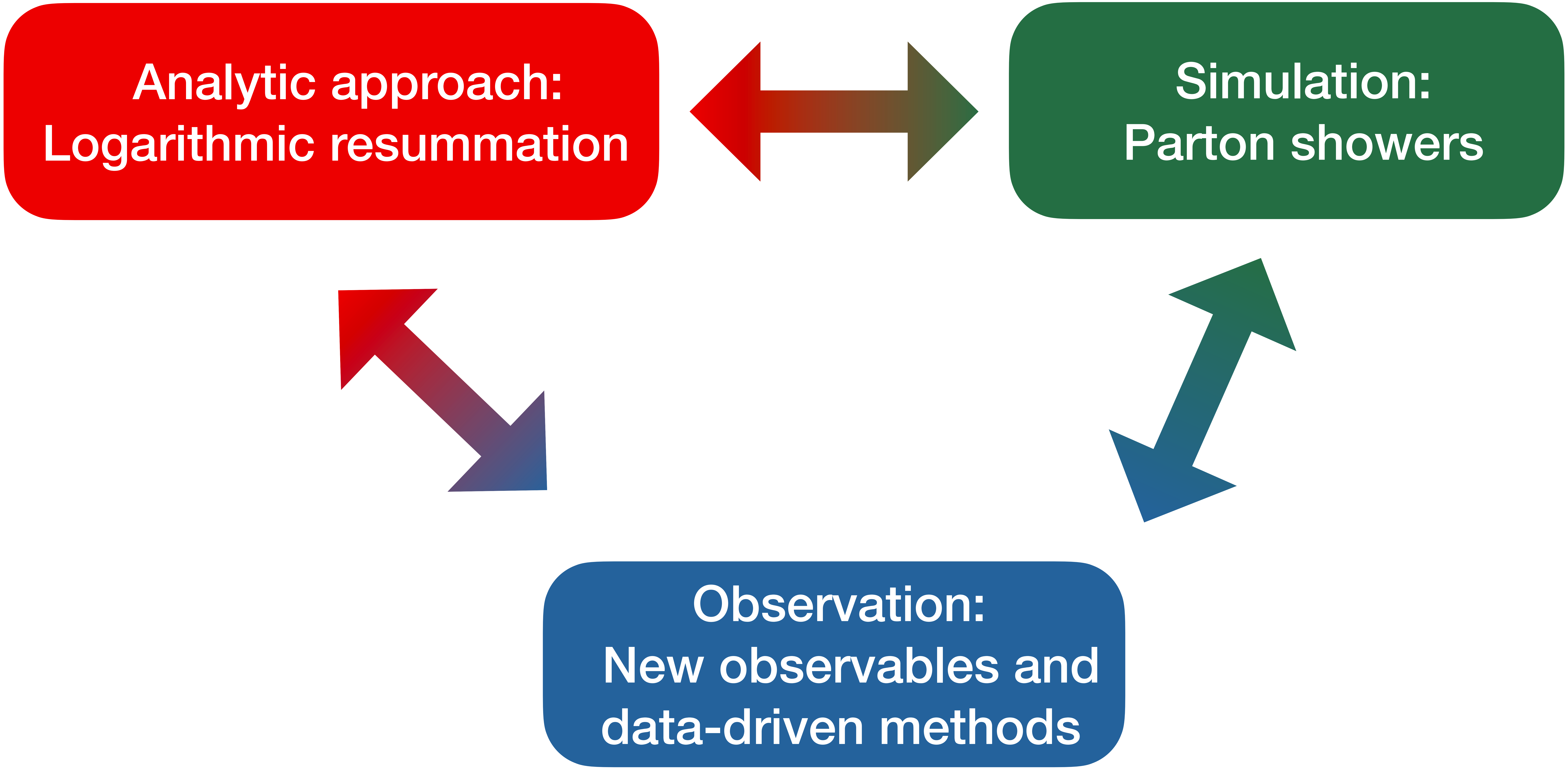
[van Beekveld, ASO et al. JHEP 11 (2022) 019, JHEP 11 (2022) 020]

Azimuthal angle between leading jets



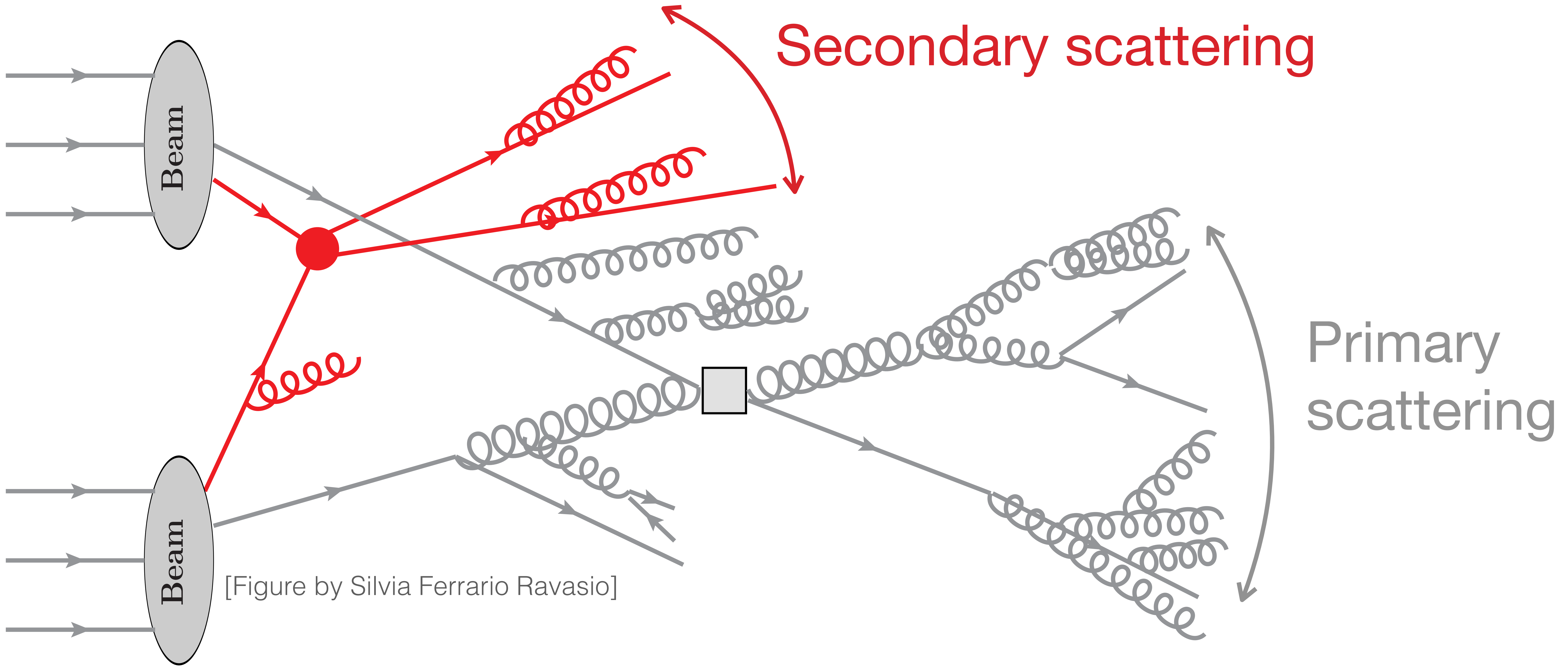
The new generation of NLL showers (see also ALARIC) opens the path towards definition of MC uncertainties

Outline of this talk



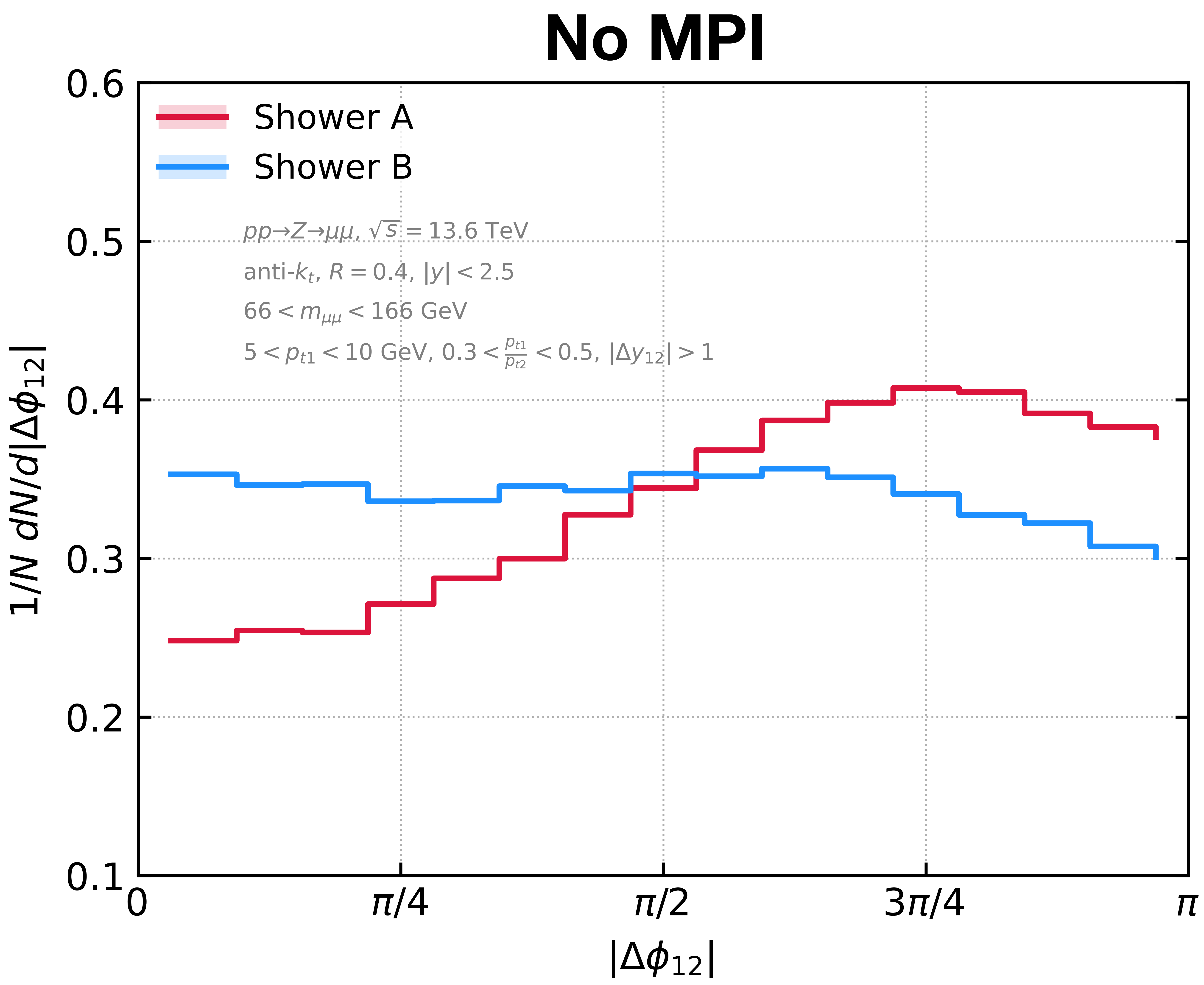
The role of multi-parton interactions

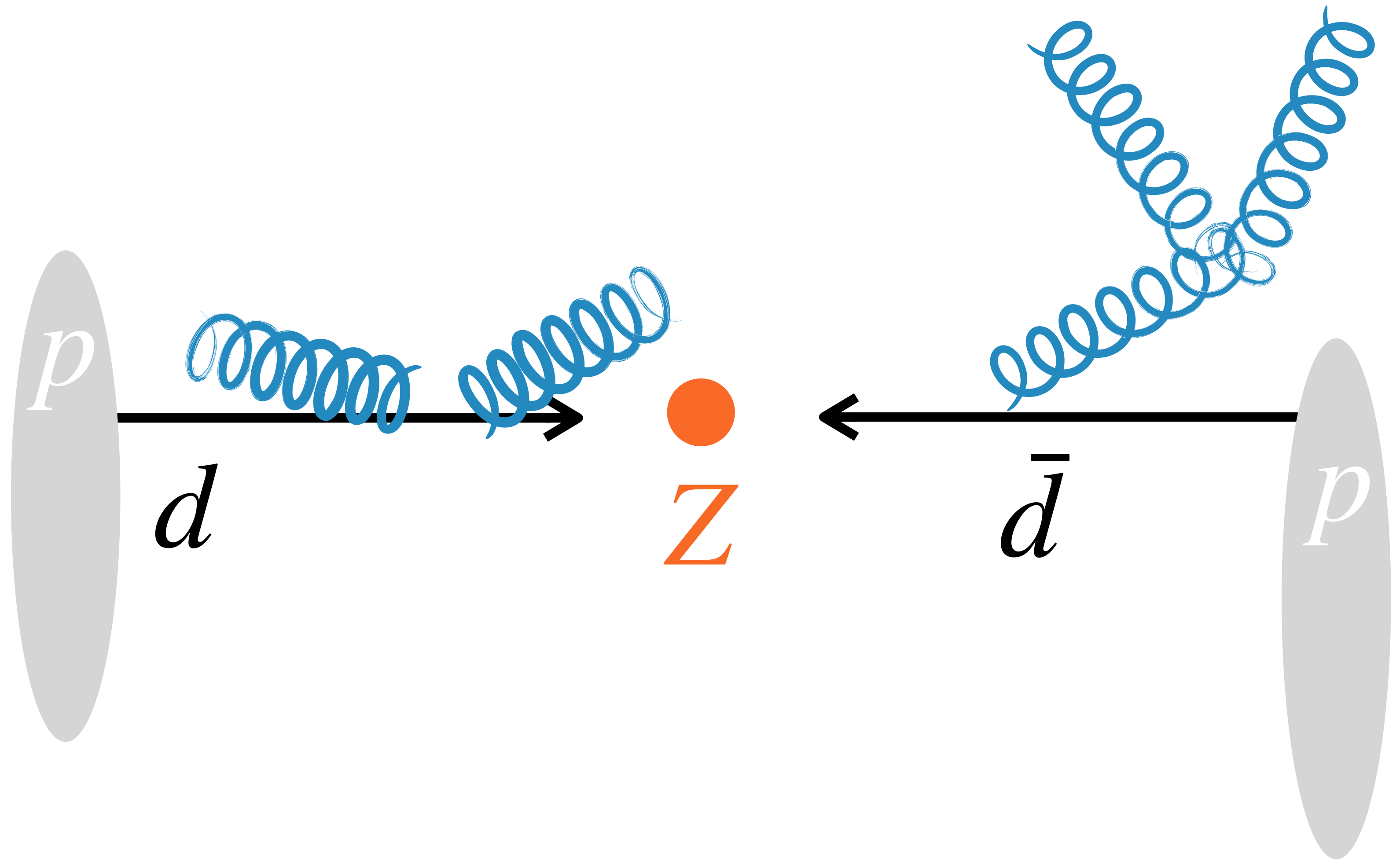
In a typical LHC event multiple parton-parton interactions occur



The description of MPIs is beyond pQCD and modelled in all MCs

The role of multi-parton interactions in low-p_t jets





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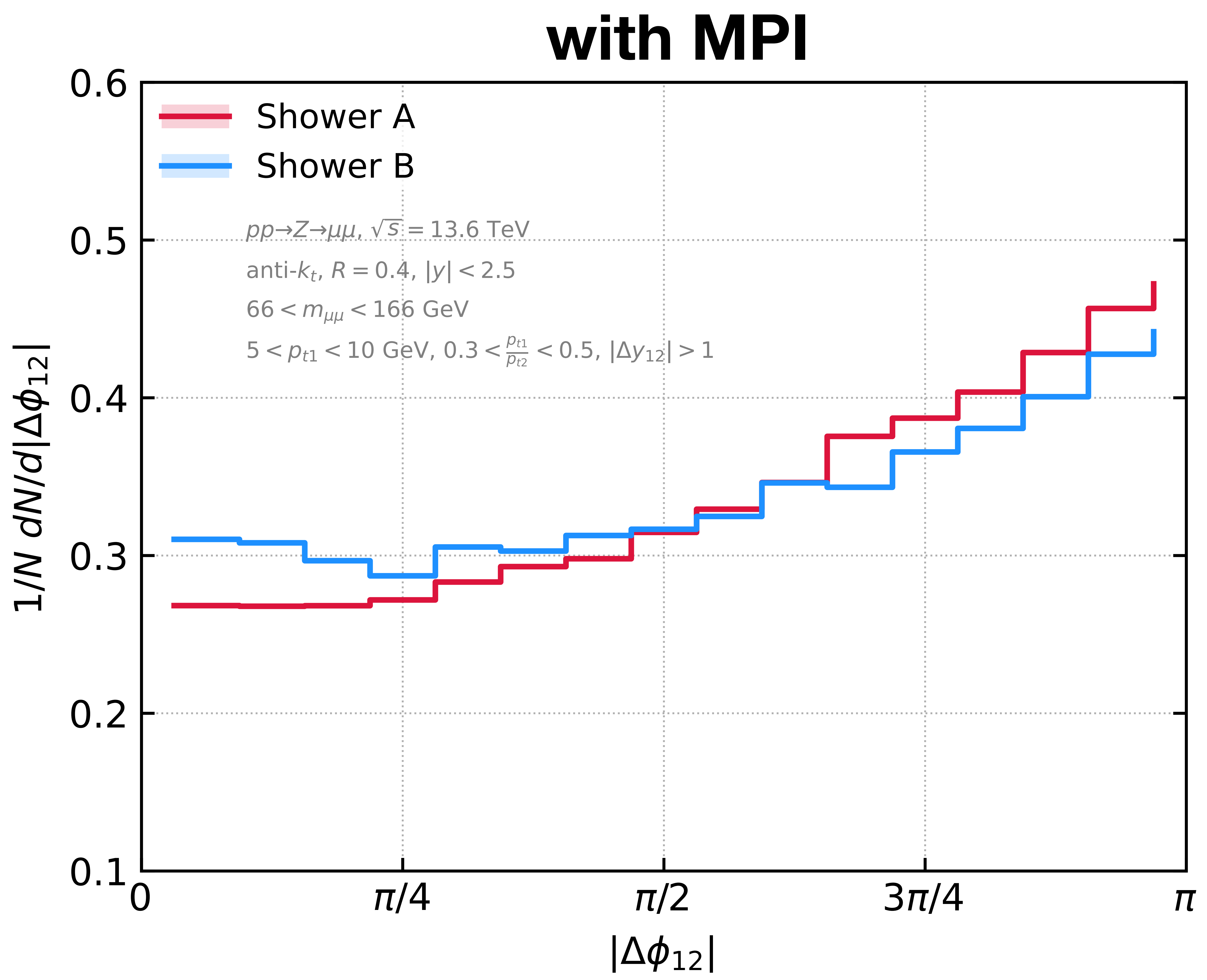
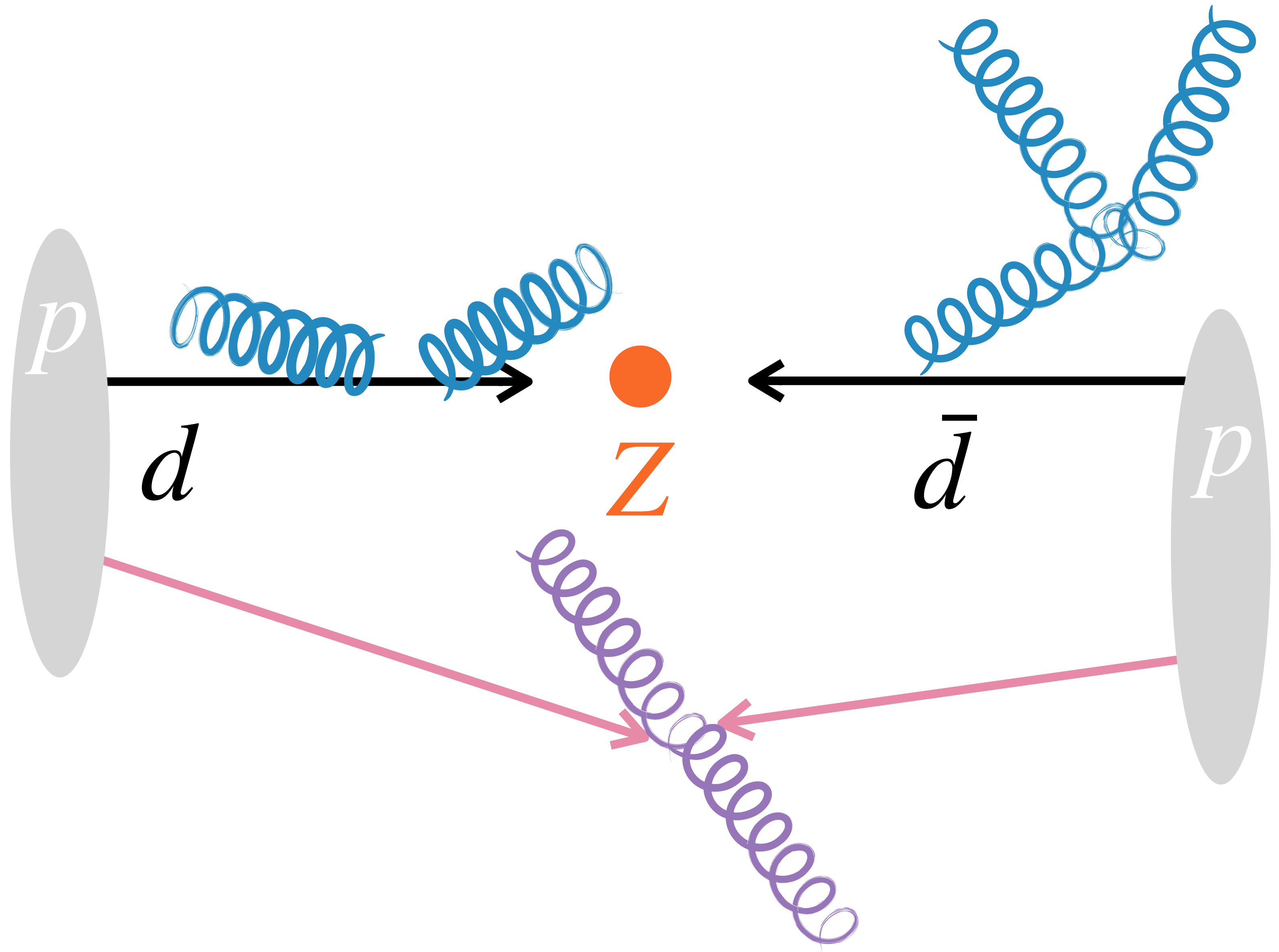
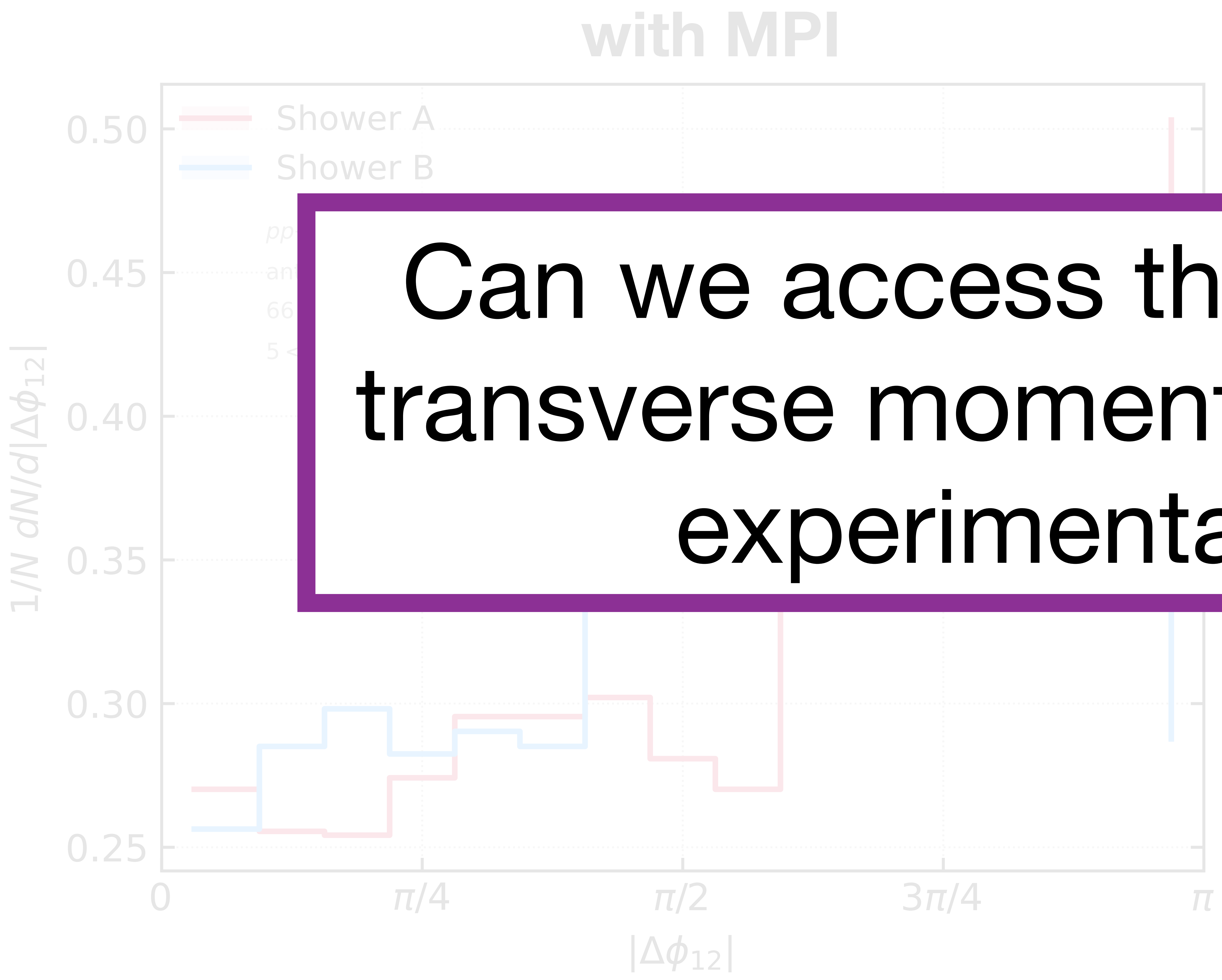
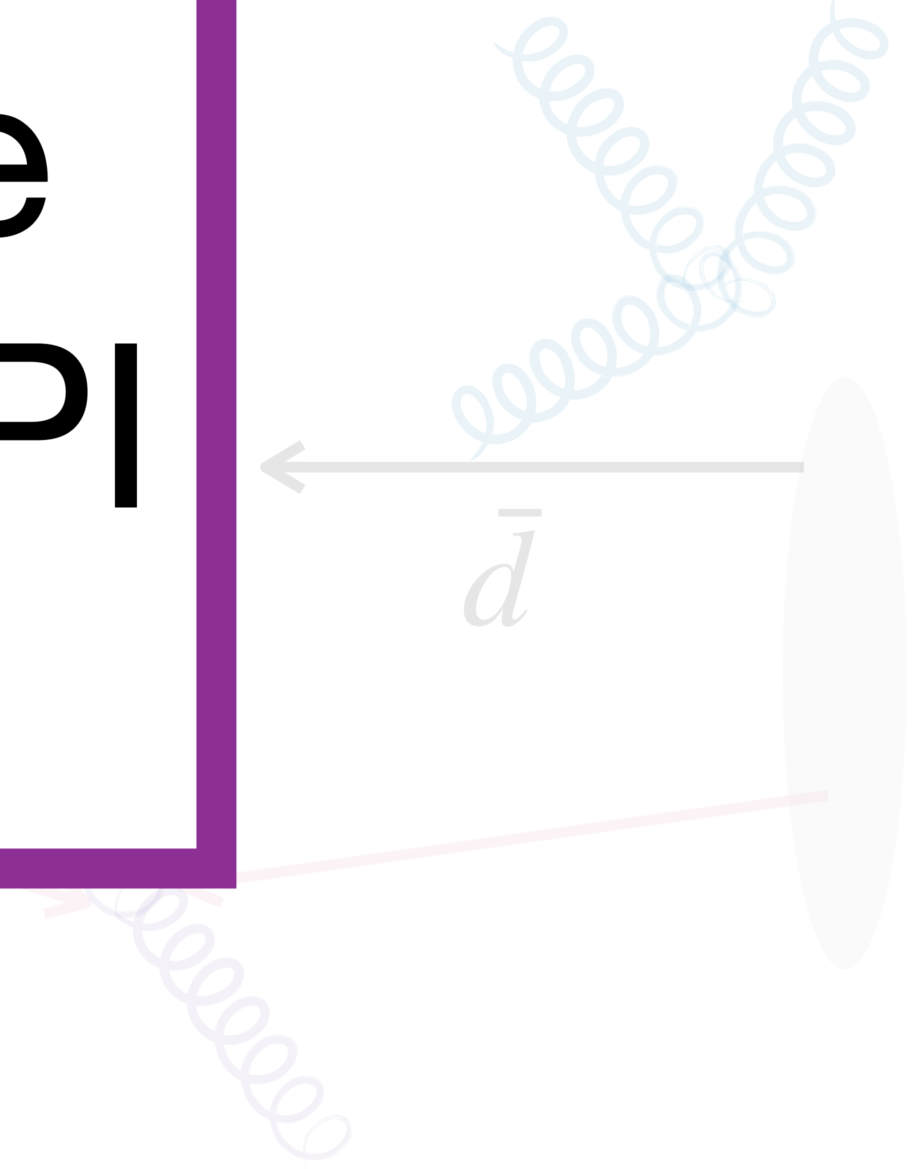




The role of multi-parton interactions in low-p_t jets



Can we access the average transverse momentum of MPI experimentally?

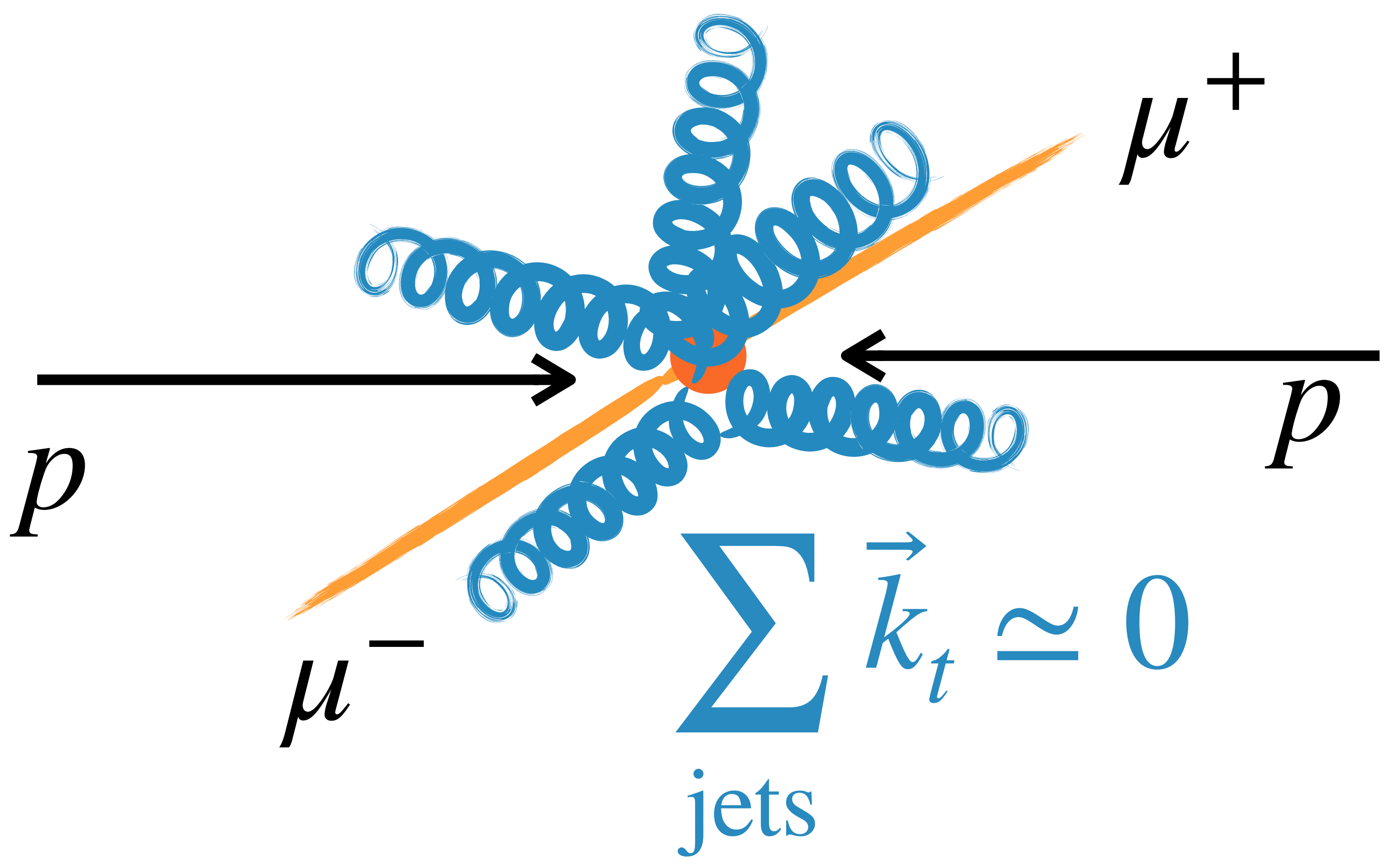


A new strategy: tone down the primary scattering

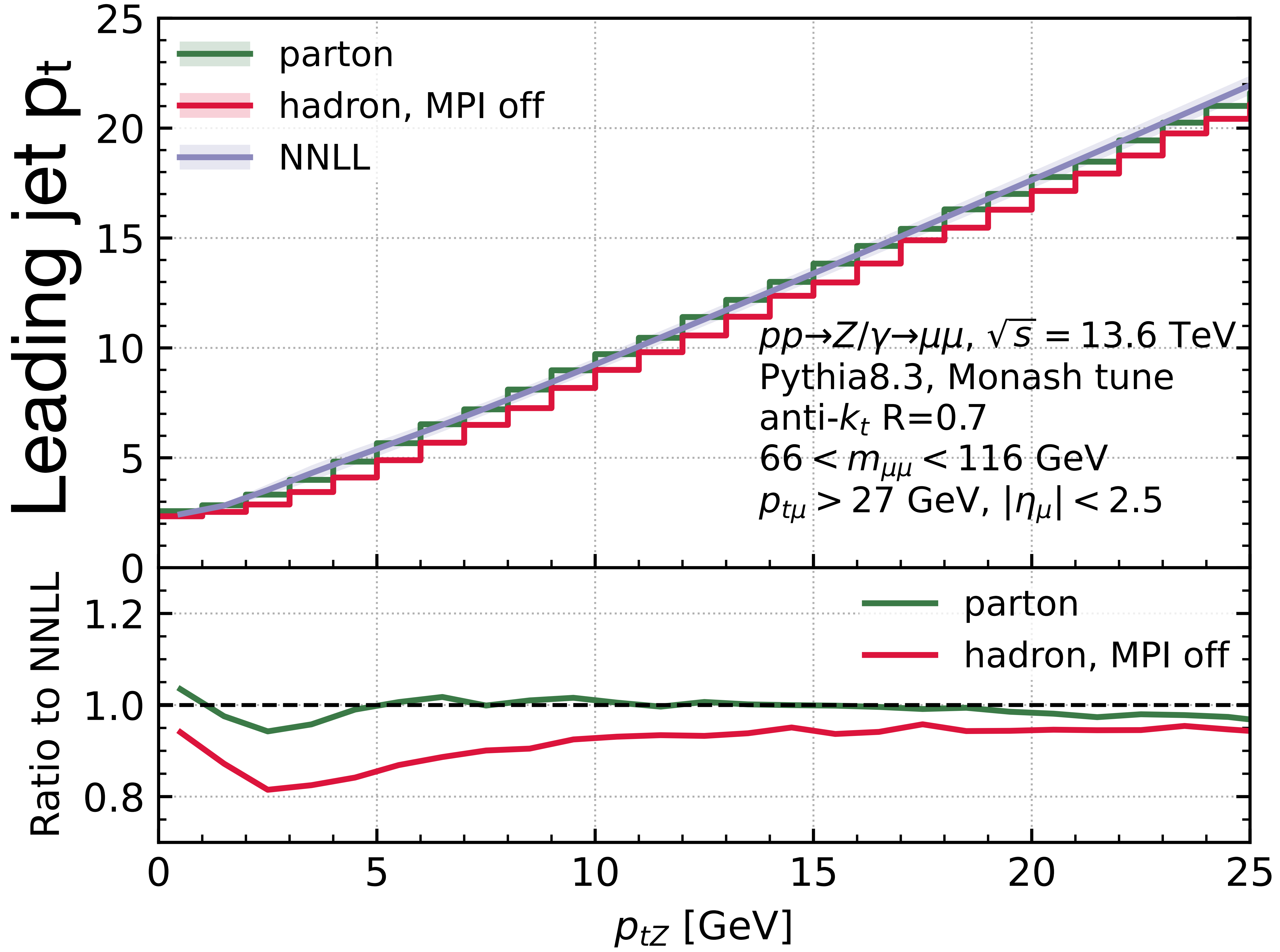
[Andersen, Monni, Rottoli, Salam, ASO in preparation]

We propose to measure Drell-Yan events and require $p_{tZ} \to 0$

In this limit, the dynamics of recoiling jets can be robustly described in pQCD



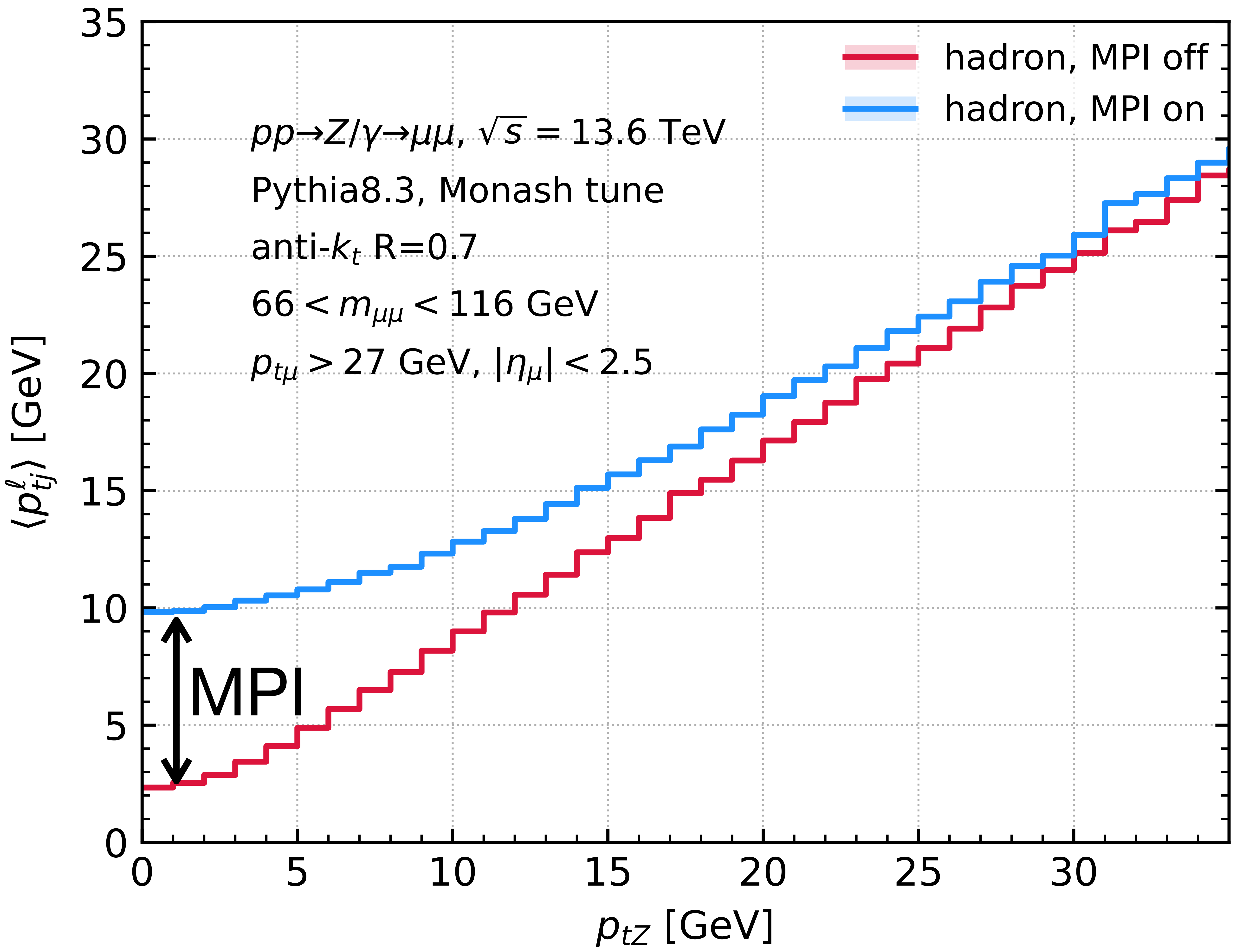
[Parisi, Petronzio, NPB 154 (1979) 427-440]



A new strategy: tone down the primary scattering

[Andersen, Monni, Rottoli, Salam, ASO in preparation]

Any observable using jets below 10 GeV is contaminated by MPI



A new strategy: tone down the primary scattering

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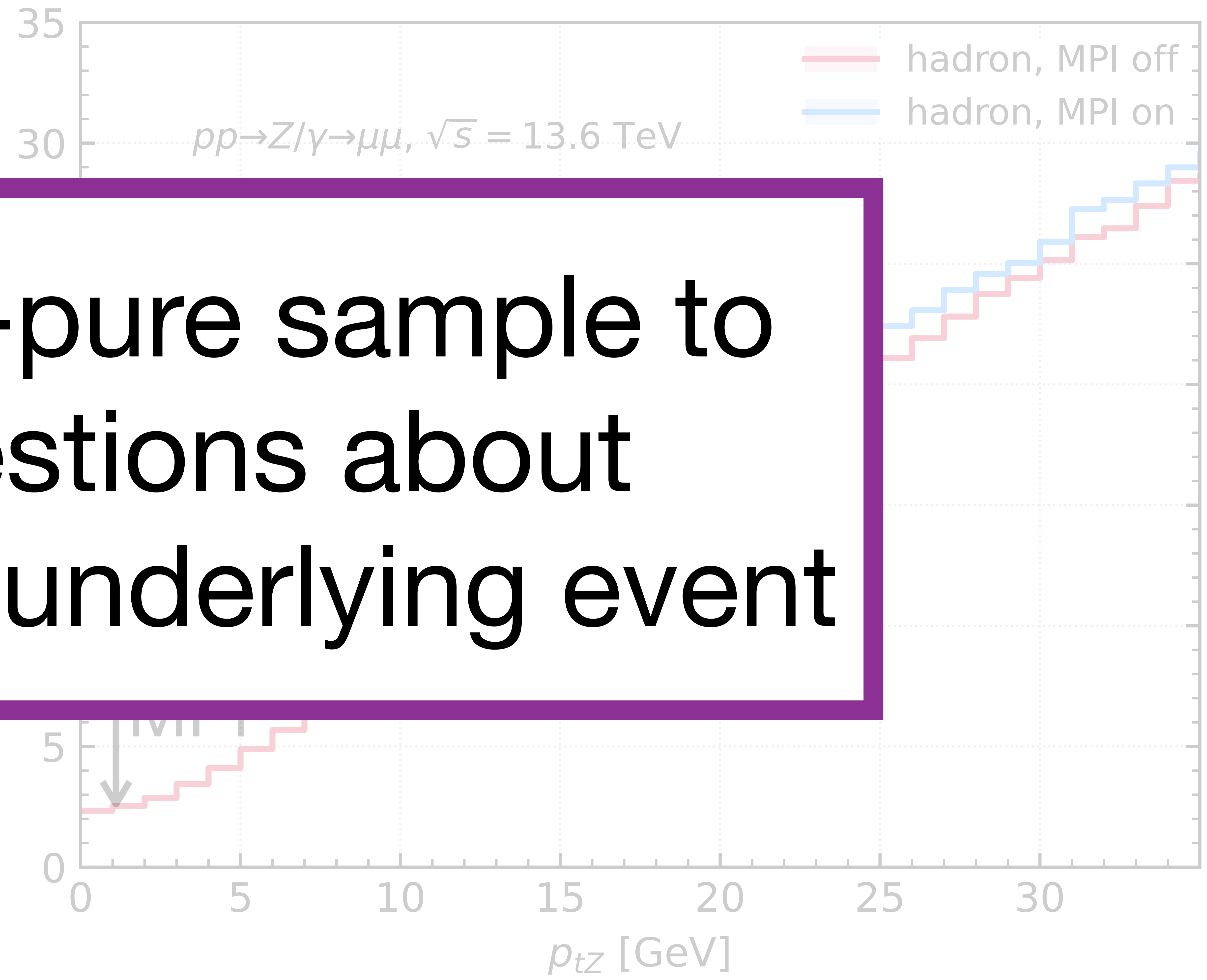
Any obse
10 GeV is



Use the quasi-pure sample to answer questions about composition of underlying event

How do these developments impact BNL physics program?

Some ideas about the EIC

The EIC will collide electron and protons at $20 \lesssim \sqrt{s} \lesssim 140 \text{ GeV} \approx 0.01\sqrt{s}_{\text{LHC}}$

$$\ln \frac{Q}{\lambda_{\text{QCD}}}\bigg|_{\text{EIC}} \ll \ln \frac{Q}{\lambda_{\text{QCD}}}\bigg|_{\text{LHC}} \implies$$ smaller impact of resummation

However, the EIC provides a clean environment and 10 fb^{-1} in 30 weeks

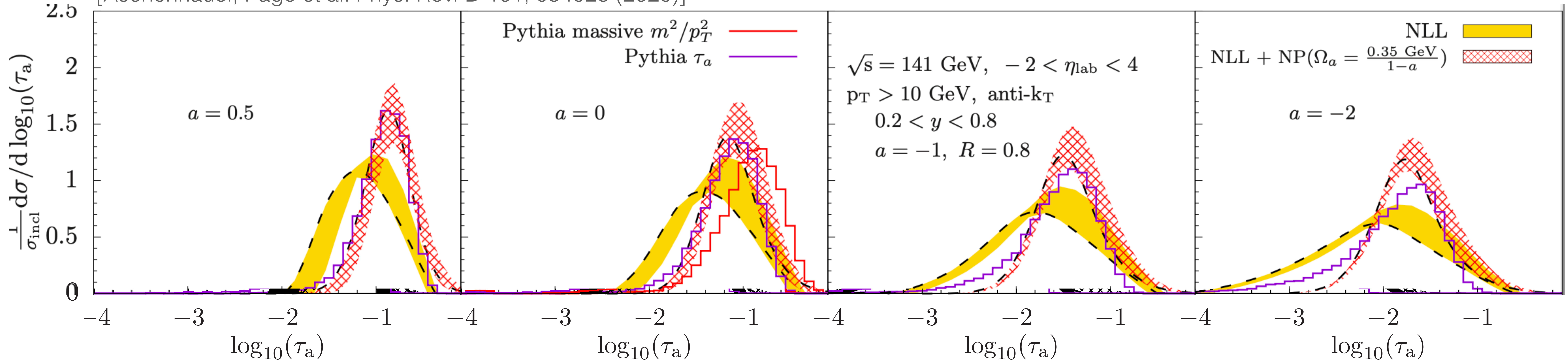
The description of EIC data by an MC generator with highly-precise perturbative components can shed light on hadronisation

[Chien, Deshpande et al. Phys.Rev.D 105 (2022) 5, L051502]

Some ideas about the EIC

1 NLL showers for DIS are in the PanScales roadmap

[Aschenhauer, Page et al. Phys. Rev. D 101, 054028 (2020)]

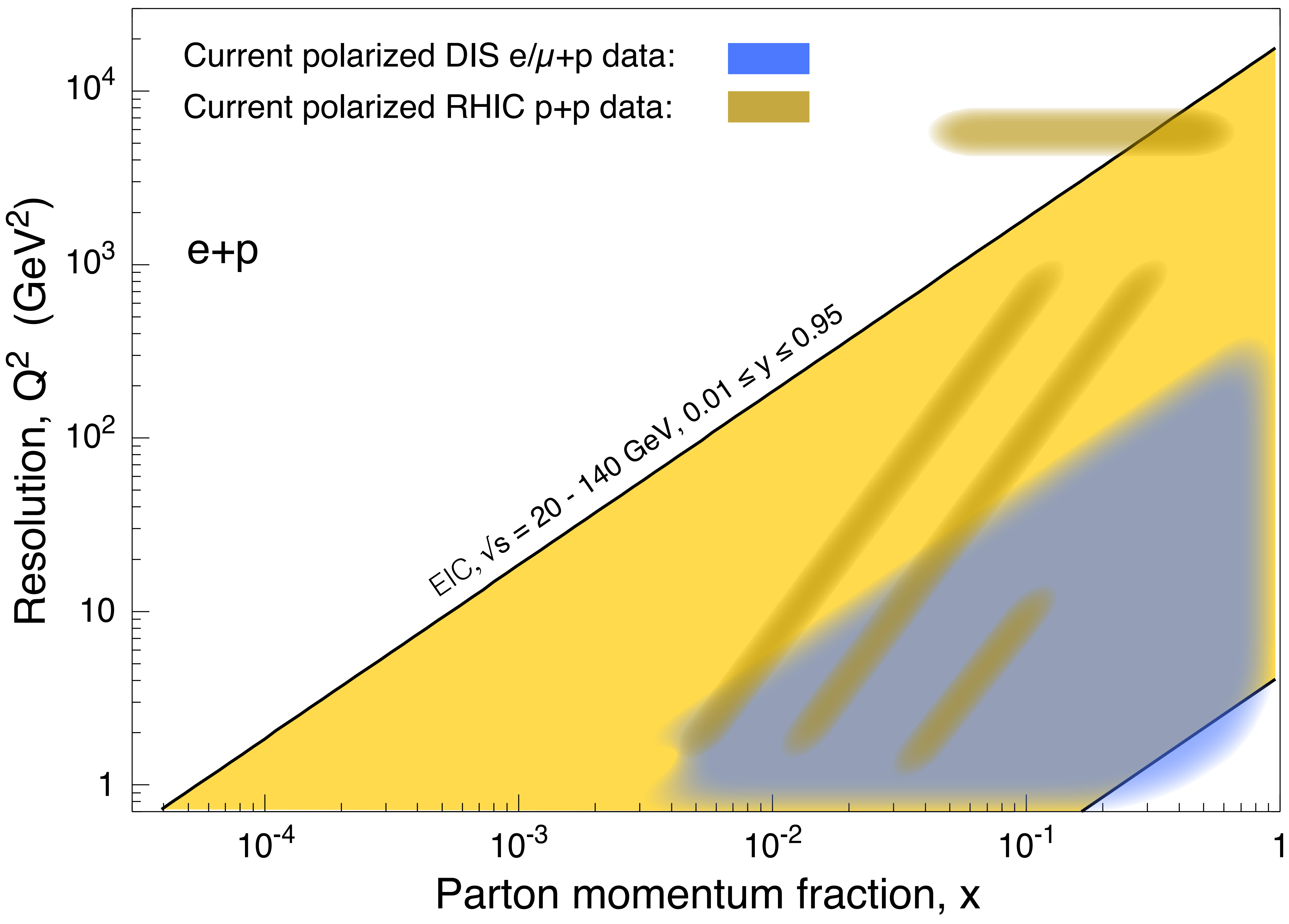


Spin correlations framework could be extended to polarised beams

Since $p_{t,\text{jet}}$ is relatively small, must include heavy quark masses (ongoing)

Some ideas about the EIC

2 Kinematic regime at the boundaries of collinear and TMD factorisation



How to incorporate small-x

$$\ln \frac{s}{Q^2}$$

resummation into PanScales?
Interplay with saturation dynamics?

[Seminal work by Caucal, Hatta, Mehtar-Tani, Salazar, Schenke, Venugopalan…]

Summary and outlook

- The HL-LHC will collect 20x more data in the coming years
- Key to discovery potential is a precise understanding of QCD dynamics
- We are at the dawn of the parton shower *revolution*, i.e. logarithmic resummation as a design guideline
- The development of highly-accurate parton showers benefits all colliders

Long term goal: a unified picture of QCD branchings from EIC to LHC (pp and heavy-ions)