Testing Hadronisation Models with the CEPC

A (small) selection of topics

Peter Skands (Monash U)

Nonperturbative QFT remains among the most fundamental problems in physics

A day will come when someone (claims to) have a solution, or at least a systematically improvable approximation

(+ LHC ⟷ further refinements of phenomenological models of NP QCD)

Program of high-precision QCD measurements at CEPC/FCC-ee

Ultimate trial by fire for any future treatment of confinement in high-energy processes

Basic requirements:

Measure effects of order Λ_{QCD} with high precision

Disentangle different "tracers": strangeness, baryons, mass, & spin → **PID**

Other aspects:

$H \to gg$, Colour Reconnections (in Z, WW, ttbar), and Power Corrections

Interplay with other components of physics program; α_s measurements; $\gamma\gamma$ collisions

CoEPP MCnet

CEPC Workshop

November 2018, IHEP, Beijing

QCD THEMES @ CEPC

Measure alphaS

High-Precision Z (and W) widths

High-Precision Event Shapes, Jet Rates, … (IR safe observables sensitive to alphaS)

Single-Inclusive Hadron Production and Decays

Fragmentation Functions; Hadron Spectra; (+ polarisation)

Exotic /rare hadrons, rare decays, …

+ Interplay with flavour studies (+ Interplay with DM annihilation)

Understanding Confinement (Multi-hadronic / Exclusive)

In high-energy processes → hadronisation

Hadron correlations, properties with respect to global ("string") axes

Dependence on (global and local) environment (distance to jets, hadronic density, flavours)

Power Corrections / Hadronisation Corrections

Interplay with high-p_T physics program

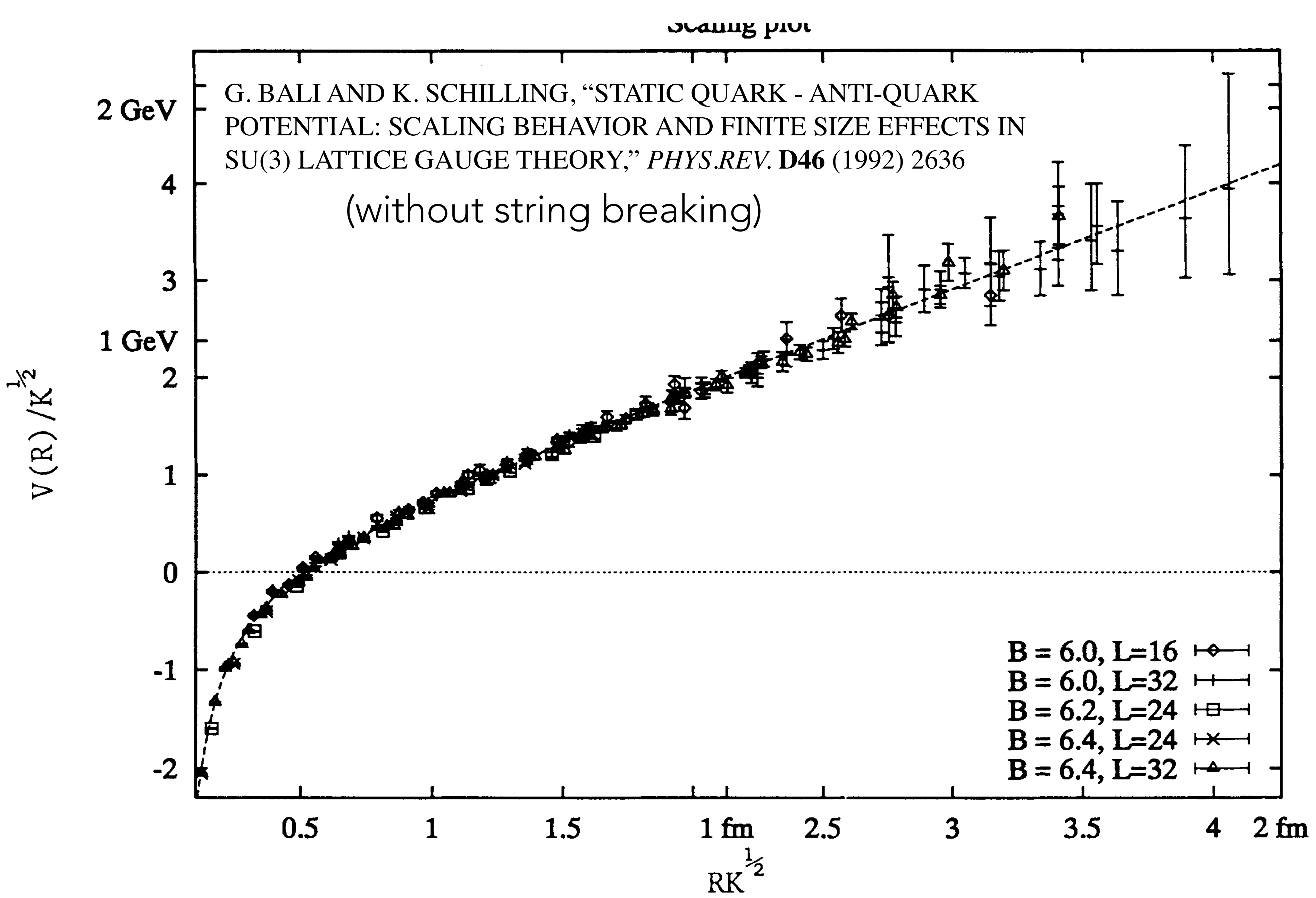
Low-Q region of event shapes, jet rates, jet substructure; jet flavour tagging, …

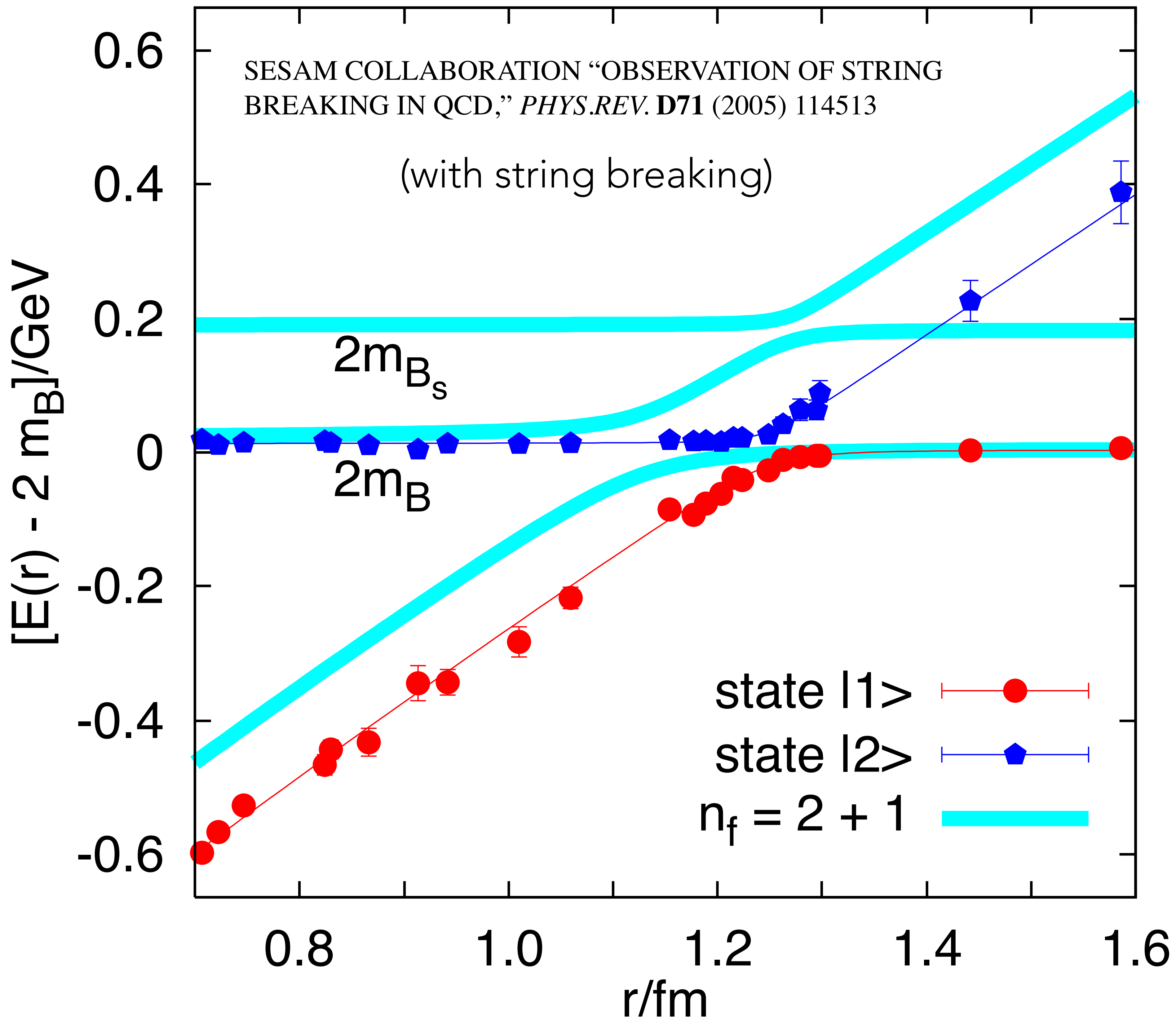
Crucial for alphaS measurements; also for jet calibration?

The "string tension" κ ~ 1 GeV/fm ~ 0.2 GeV² ~ (0.45 GeV)²

Can be extracted from hadron spectroscopy

Also: lattice quark-antiquark potential



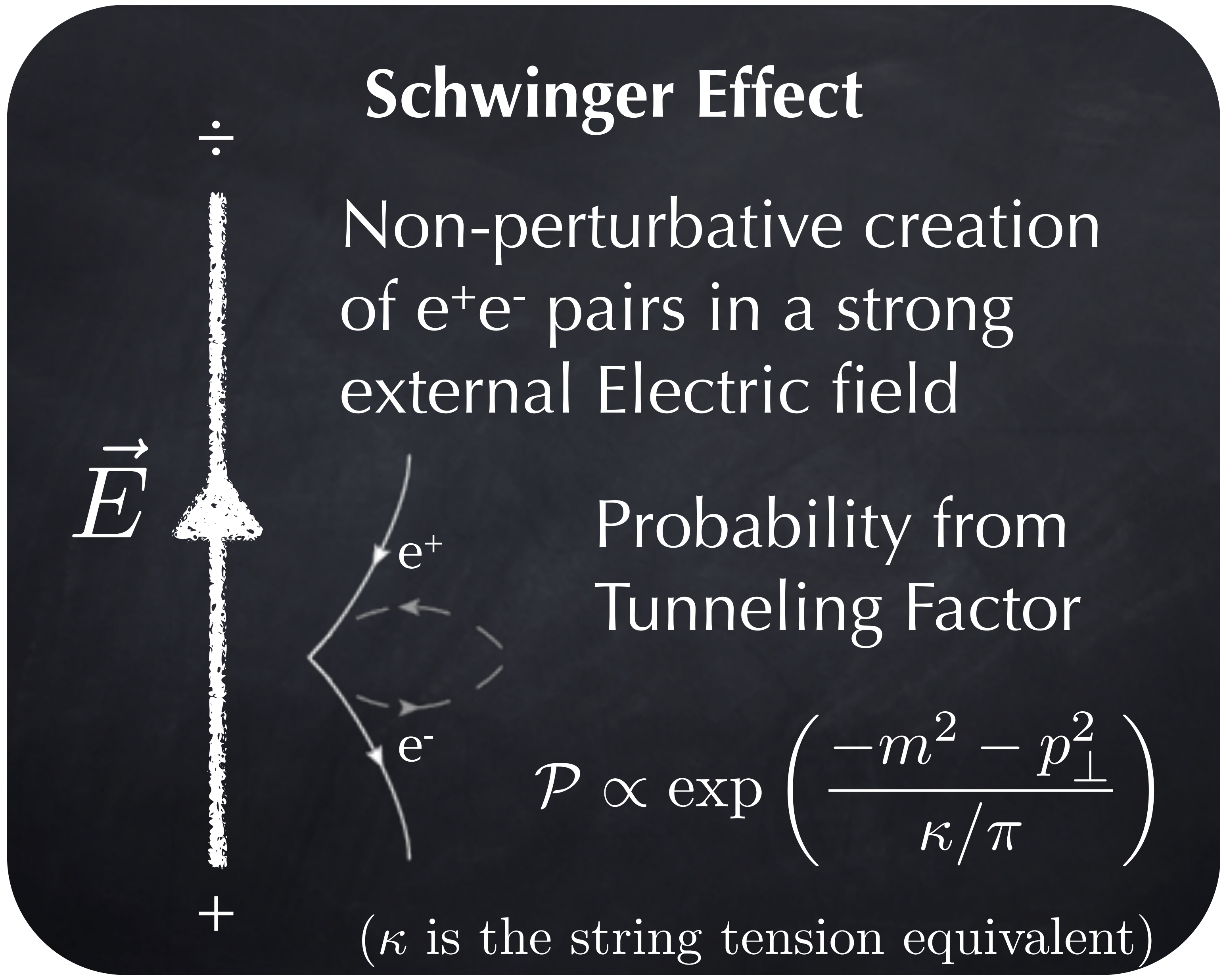


$$V(r) = -e\left(\frac{1}{r} - \frac{1}{r_c}\right) + \sigma\,(r - r_c)$$

J. S. SCHWINGER, "ON GAUGE INVARIANCE AND VACUUM POLARIZATION," *PHYS. REV.* **82** (1951) 664–679.

Schwinger (1951)

Non-perturbative pair creation of e^+e^- pairs in a strong external electric field



(Not observed experimentally yet, but may happen soon)

G. V. DUNNE, "NEW STRONG-FIELD QED EFFECTS AT ELI: NONPERTURBATIVE VACUUM PAIR PRODUCTION," *EUR. PHYS. J.* **D55** (2009) 327–340, 0812.3163.

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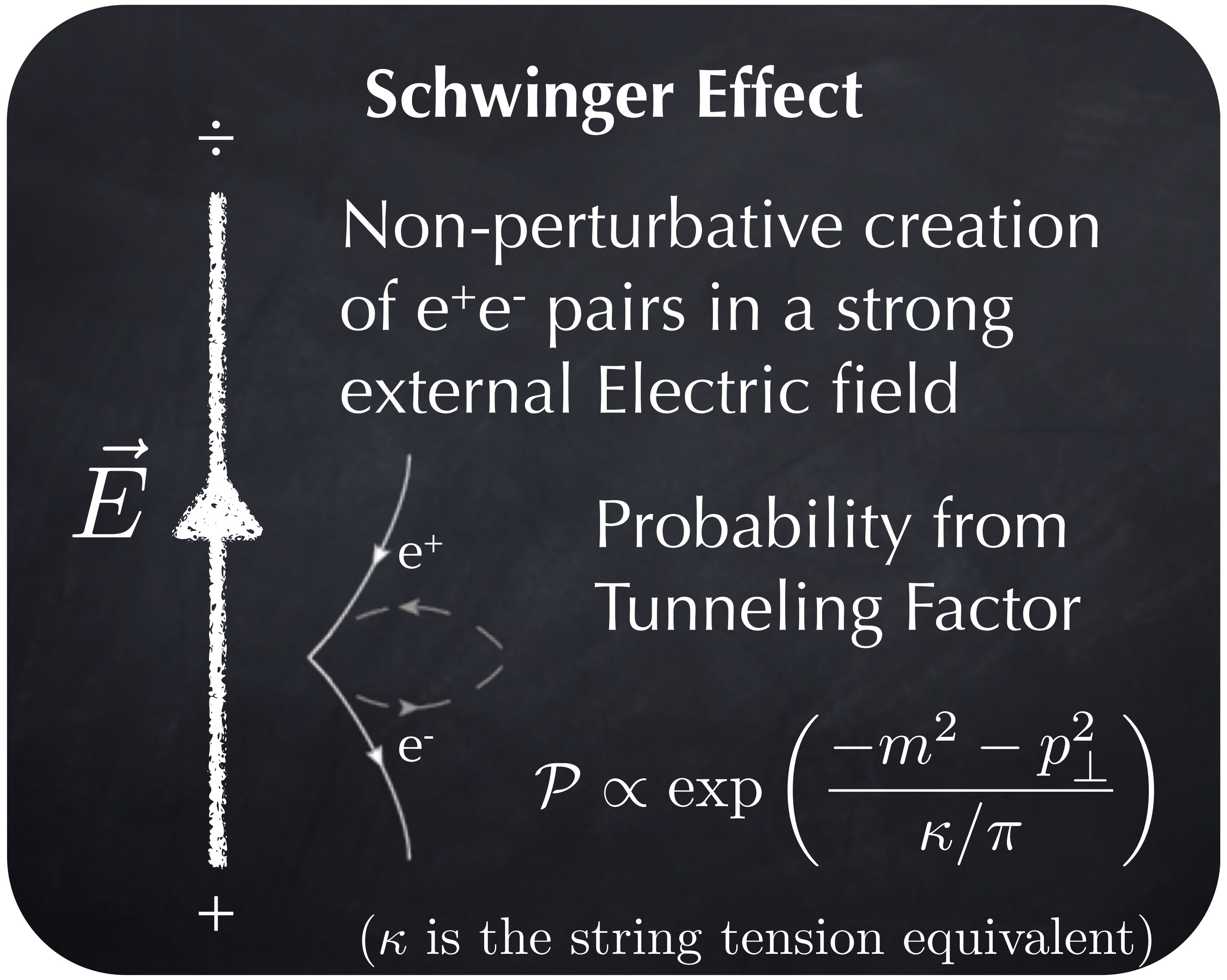


(Not observed experimentally yet, but may happen soon)

Several groups found same form for QCD at successive levels of modeling/approximation

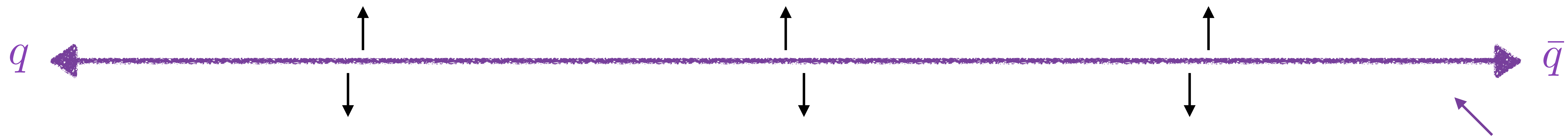
Generic prediction:

Neglecting perturbative effects, hadrons produced from a QCD string stretched between a quark and antiquark should have a universal (flavour-independent) p_T spectrum, with

$$\langle p_\perp^2 \rangle_{\mathrm{meson}} \sim 2 \langle p_\perp^2 \rangle_{\mathrm{quark}} \sim \frac{2\kappa}{\pi} \sim (0.35\ \mathrm{GeV})^2$$

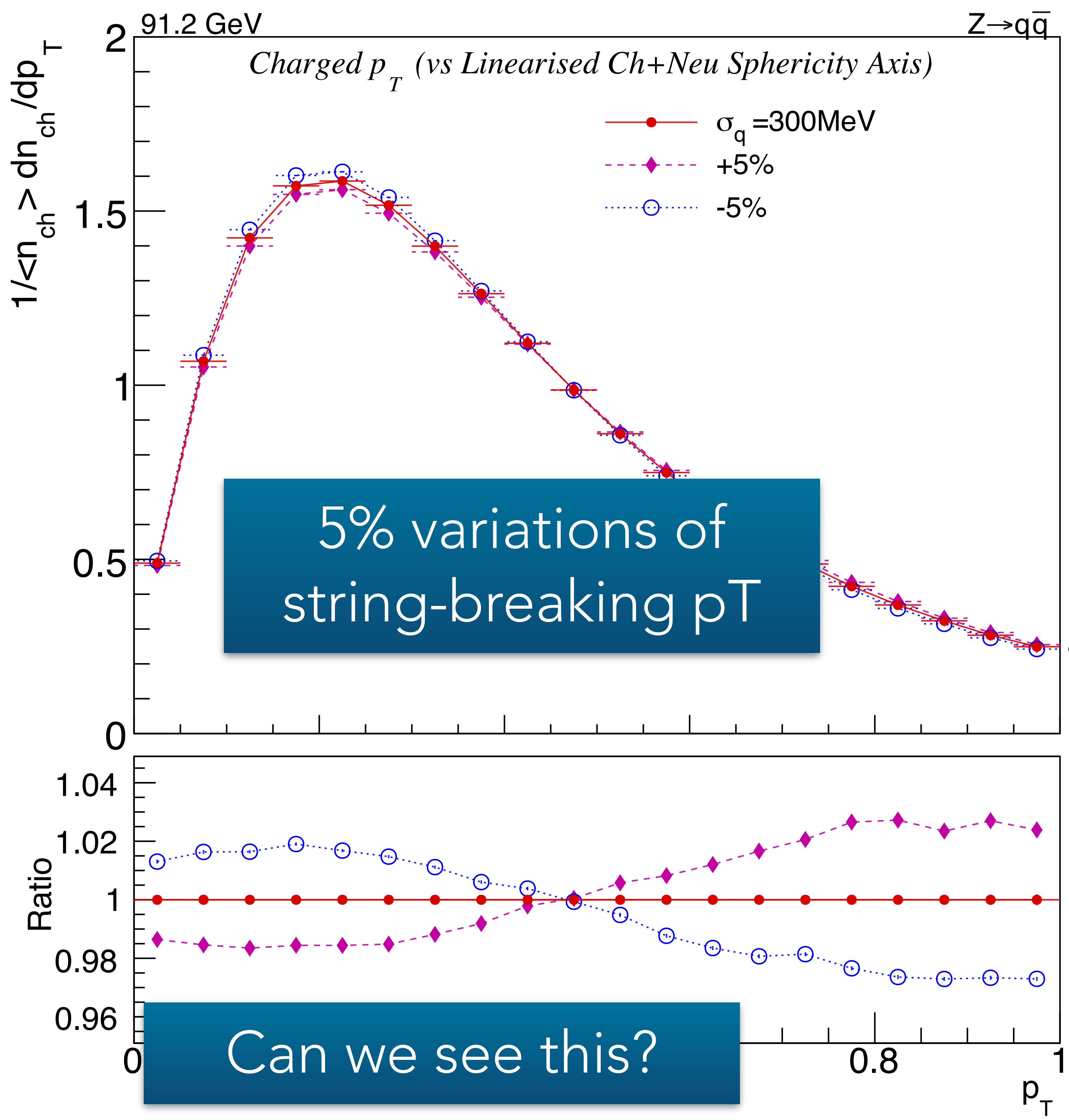
So this is an interesting scale!

(modified by perturbative effects + hadron decays)



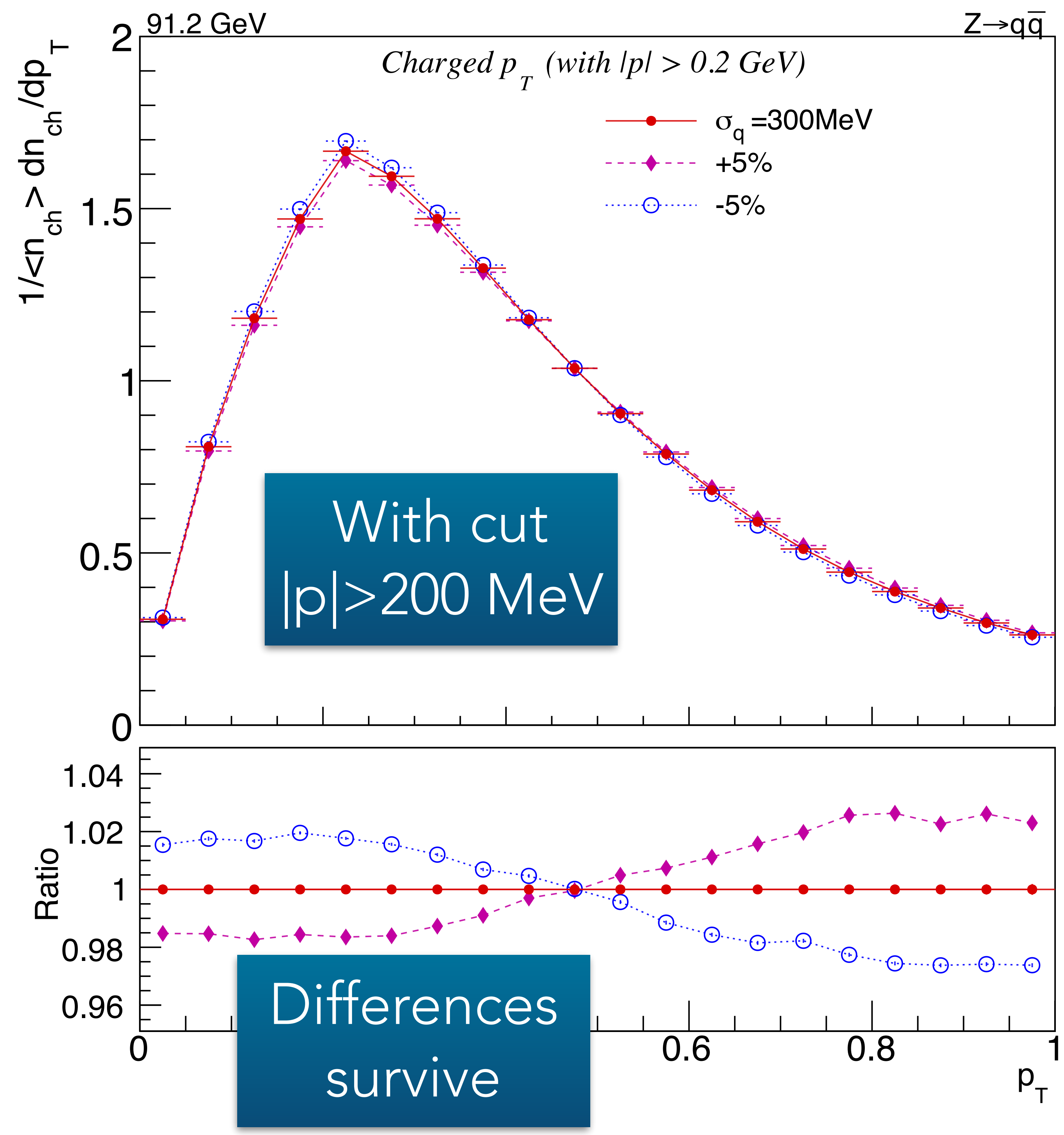
Linearised sphericity axis,
thrust axis,
2-jet axis,
...

Hadron pT spectra, transverse to dominant event axis



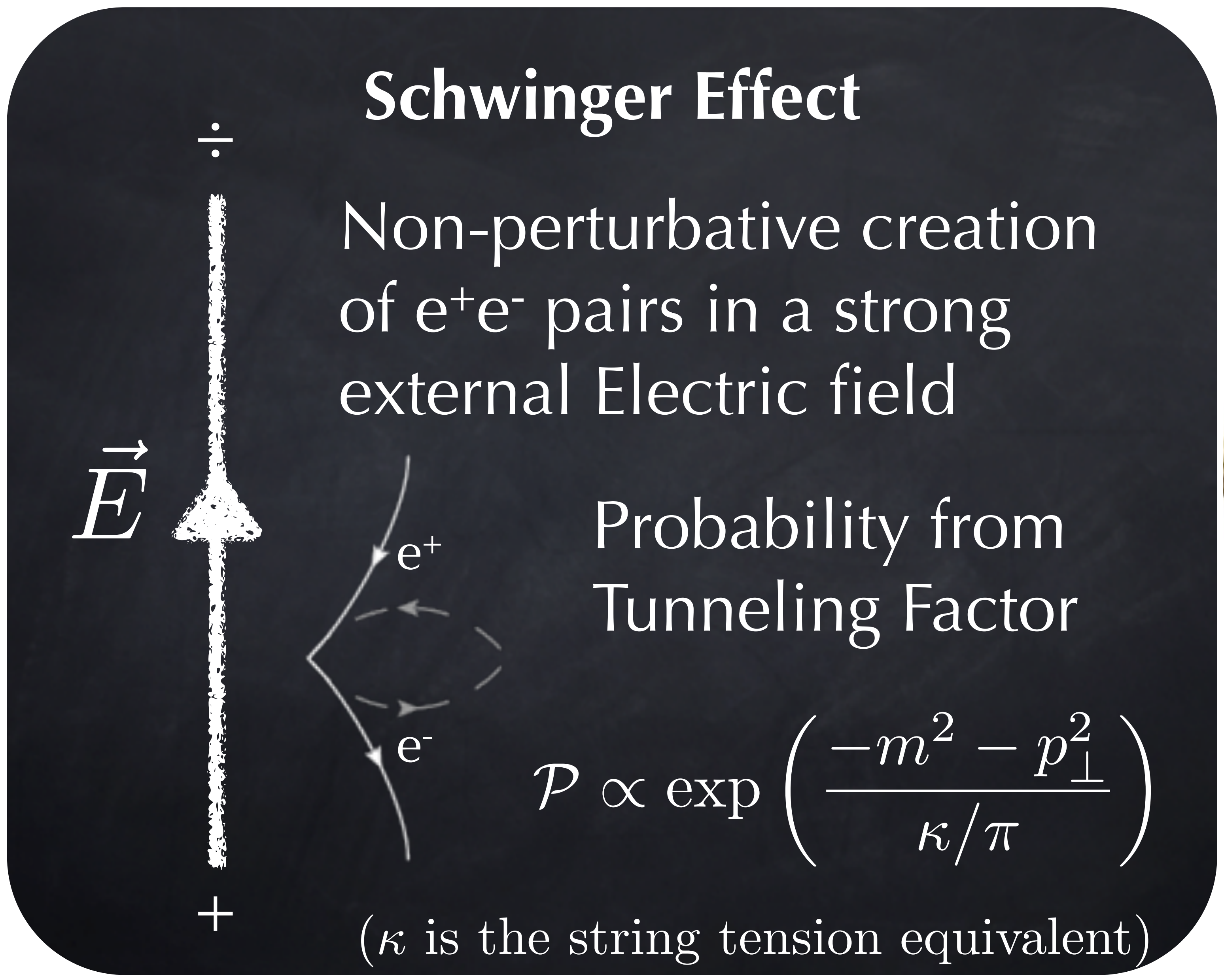
Toy Example

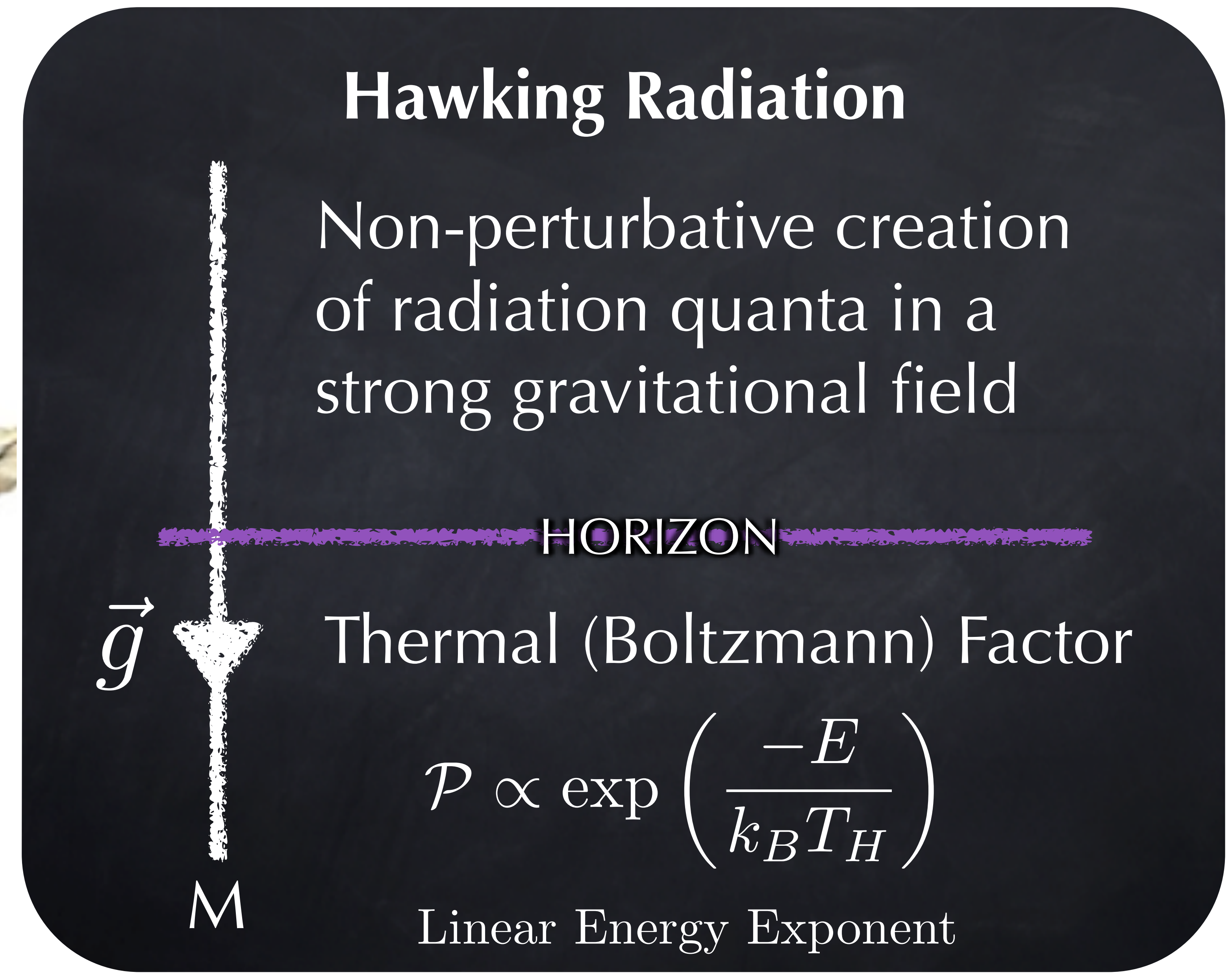
Perturbatively dominated power-law tail



Schwinger vs Hawking?

Hawking radiation: another example of spontaneous pair creation in a strong external field. This one has a horizon $\longleftrightarrow$ confinement?





Some empirical success fitting thermal spectra (Tsallis fits) to particle spectra (+ some theoretical motivations)

Mainly we just see <p_T>; tail to high p_T dominated by perturbative power law; need to **measure soft pions**

EFFECTS OF ORDER Λ_{QCD}

p_T kicks from hadronisation: Gaussian pT distribution with width ~ 300 MeV (+ ρ decays)

Difficult for any hadron to have |p| < 300 MeV.

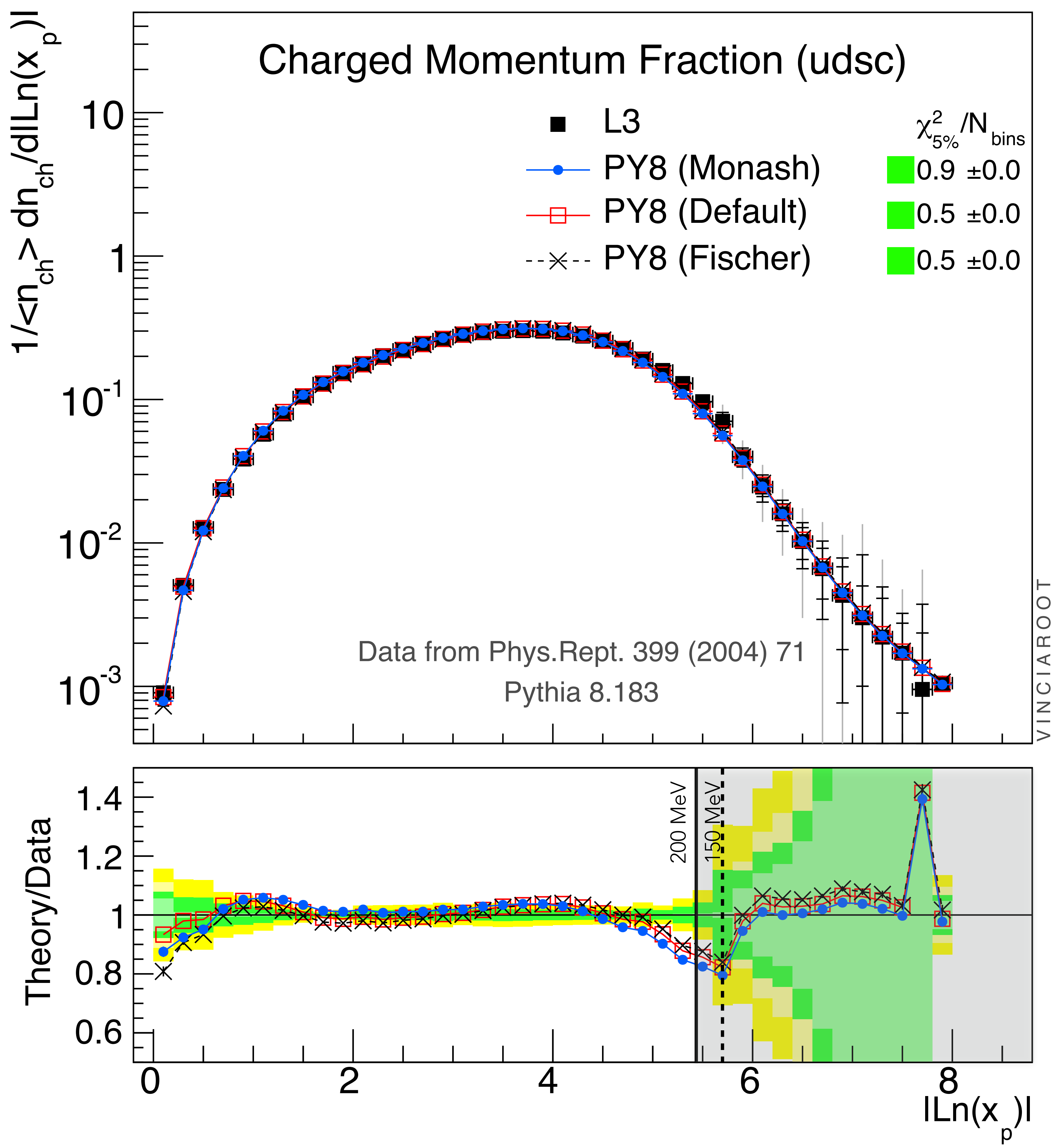
- Can you make a pion stand still?
- Non-relativistic pions

Data from both LEP and LHC indicate softer pion spectrum

Cut at |p| = 200 MeV makes this a bit tough to examine clearly

- 3 hits down to ~ 50 MeV ?
- Special runs / setups with lower thresholds?

Example from LEP



MCnet

➠ FRAGMENTATION FUNCTIONS

(see FCC-ee QCD workshops & writeups)

S. Moch (& others): field now moving towards NNLO accuracy: **1% errors** (or better)

FFs from Belle to FCC-ee *[A. Vossen]*

Precision of TH and EXP big advantage

Complementary to pp and SIDIS

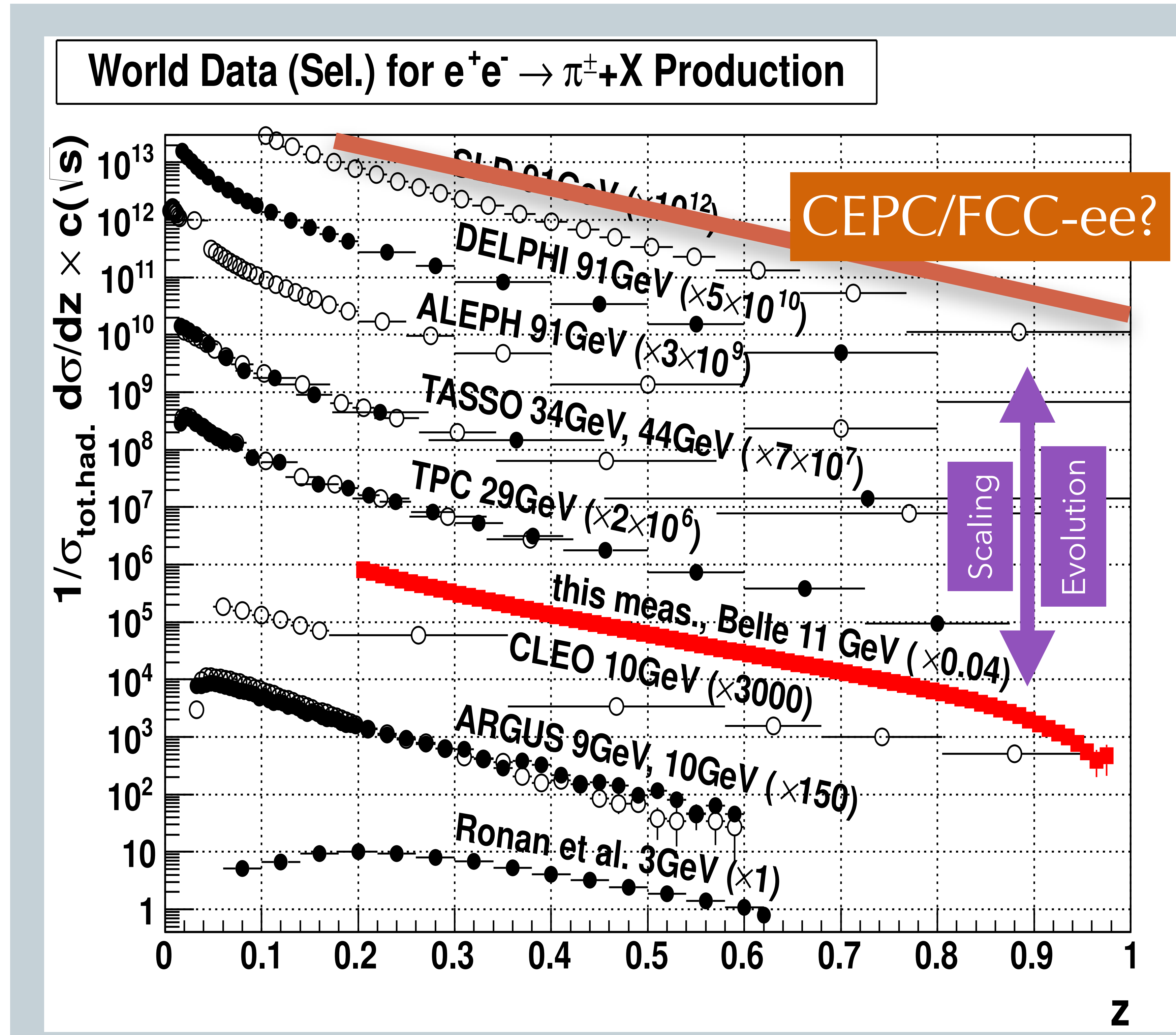
FF Evolution: ⟶

Belle has CEPC-like stats at 10 GeV.

CEPC? very fine binning all the way to z=1 with <1% |p| resolution (expected)

Flavour structure for FFs of hyperons and other hadrons that are difficult to reconstruct in pp and SIDIS.

➠ Particle Identification capabilities.



Low Z: Higher ee energy (than Belle) → smaller mass effects at low z.

3 tracker hits down to 30-40 MeV allows to reach $z = 10^{-3}$ ($\ln(z) = -7$)

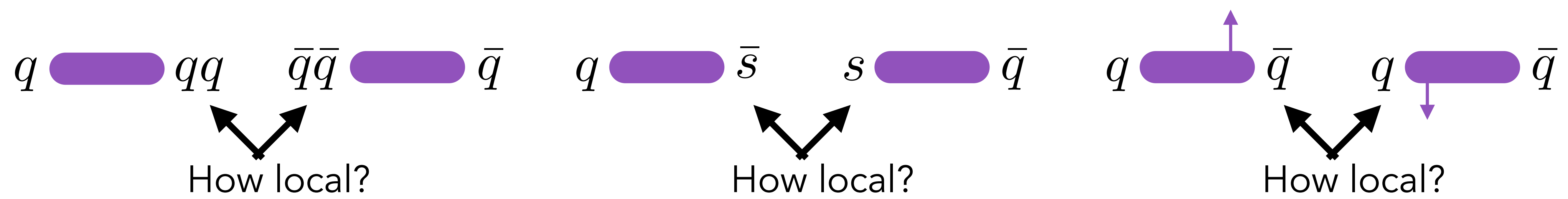
Kluth: if needed, could get O(LEP) sample in ~ 1 minute running with lower B-field

gluon FFs, heavy-quark FFs, p_T dependence in hadron + jet, polarisation,…

(see FCC-ee QCD workshops & writeups)

Octet neutralisation? (zero-charge gluon jet with rapidity gaps) → **neutrals**
Colour reconnections, glueballs, …

Leading baryons in g jets?
(discriminates between string/cluster models)
high-|p| baryons



Further precision non-perturbative aspects

Baryon-Antibaryon correlations: how local is hadronisation?

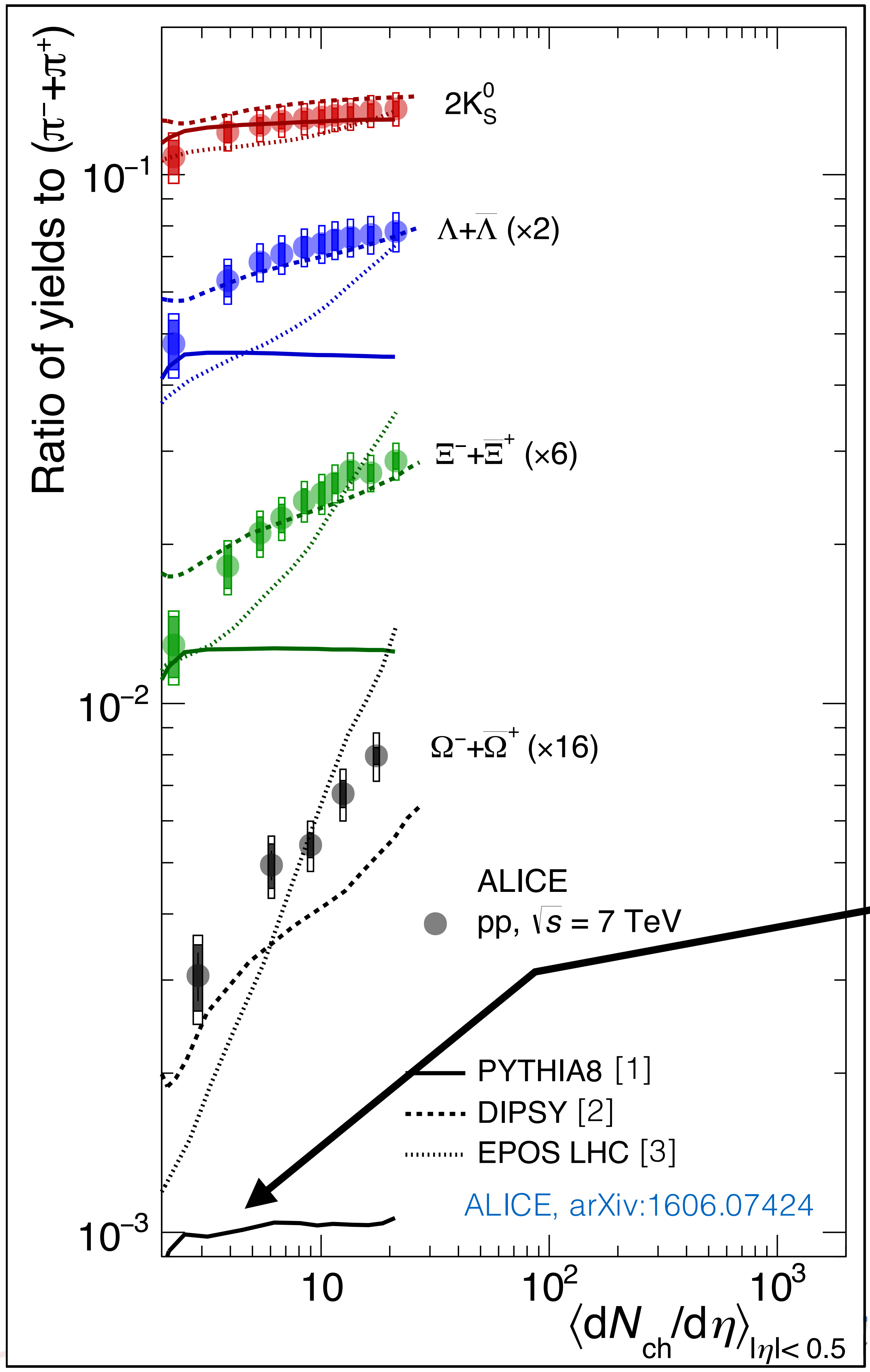
Kluth: both OPAL measurements were statistics-limited; would reach OPAL systematics at 10^8 Z decays (→ 10^9 with improved systematics?)

+ Strangeness correlations, p_T, spin/helicity correlations (“screwiness”?)

Bose-Einstein Correlations & Fermi-Dirac Correlations

Identical baryons! (pp, ΛΛ) ; highly non-local in string picture

W. Metzger: remaining Fermi-Dirac radius puzzle: correlations at LEP across multiple experiments & for both pp and ΛΛ → 0.1 fm << r_p (MC dependent? Were pΛ cross checks ever done? see EPJC 52 (2007) 113)



D.D. Chinellato – 38th International Conference on High Energy Physics

ALICE: clear enhancement of strangeness with (pp) **event multiplicity**

Especially for multi-strange baryons

No corresponding enhancement for protons (not shown here but is in ALICE paper)

→ must really be a strangeness effect

Measurements of phi now underway

Jet universality: jets at LHC modelled the same as jets at LEP

→ Flat line ! (cf PYTHIA)

Some models anticipated the effect!

DIPSY (high-tension overlapping strings)

EPOS (thermal hydrodynamic "core")

Is it thermal? Or stringy? (or both?)

Basic check in ee→WW: two strings

(LEP: total Ω rate only known to ± 20%)

COLOUR RECONNECTIONS

(see FCC-ee QCD workshops & writeups)

T. Sjöstrand, W. Metzger, S. Kluth, C. Bierlich

At LEP 2: hot topic (by QCD standards): 'string drag' effect on W mass

Non-zero effect convincingly demonstrated at LEP-2

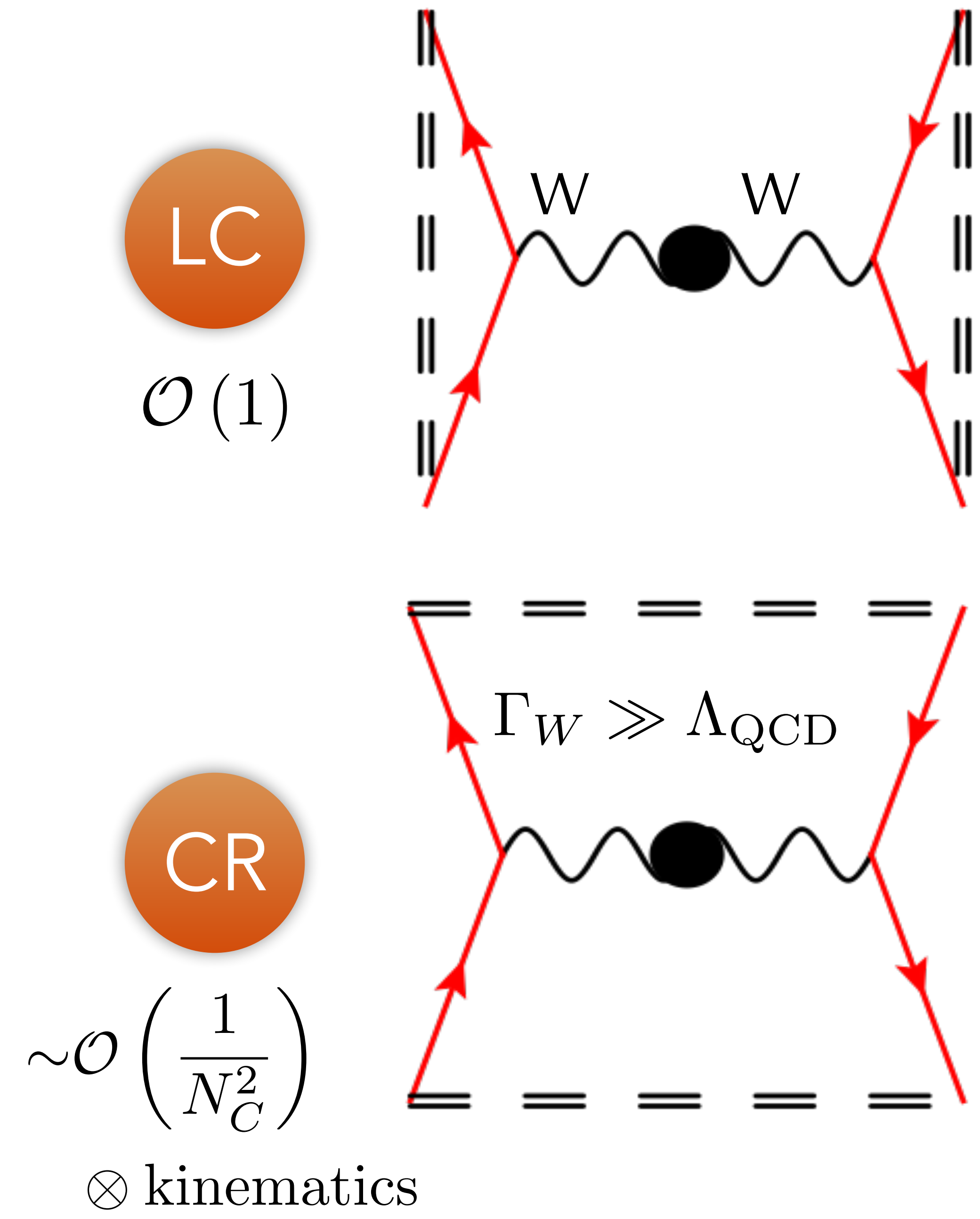
No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119]

But not much detailed (differential) information

Thousand times more WW at CEPC / FCC-ee

Turn the W mass problem around; use threshold scan + huge sample of semi-leptonic events to measure m_W

→ input as constraint to measure CR in hadronic WW



Has become even hotter topic at LHC

It appears jet universality is under heavy attack.
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

High-stats ee → other side of story

Also relevant in (hadronic) ee→tt, and Z→4 jets

+ Overlaps → interactions? increased tensions (strangeness)? breakdown of string picture?

Overviews of recent models: arXiv:1507.02091 , arXiv:1603.05298

Multi-jet events

At LEP: kicked off the subfield of matrix-element matching & merging

Transformed QCD collider phenomenology from being one of fixed-order vs Monte Carlo calculations to being fixed-order **+** Monte Carlo.

Blazed the trail for LHC state of the art: **Multi-jet NLO merging**

P Richardson
(parton showers since LEP)

- For the first time in many years more work on the accuracy of the parton-shower algorithms.
- Needed as we go to higher accuracy for the matrix elements.
- $1/N_c$ (Plätzer, Sjödahl JHEP 1207 (2012) 042), (Nagy, Soper, JHEP 1507 (2015) 119)
- Subleading logs (Li, Skands, arXiv:1611.00013)
- This is the area where there is probably the greatest potential for improvement.
- If we can consistently improve the logarithmic accuracy.

Expect 2nd-order showers within the next decade, screaming for "2nd-order" validations.

QUARKS AND GLUONS

G. SOYEZ, K. HAMACHER, G. RAUCO, S. TOKAR, Y. SAKAKI

Handles to split degeneracies

H→gg vs Z→qq

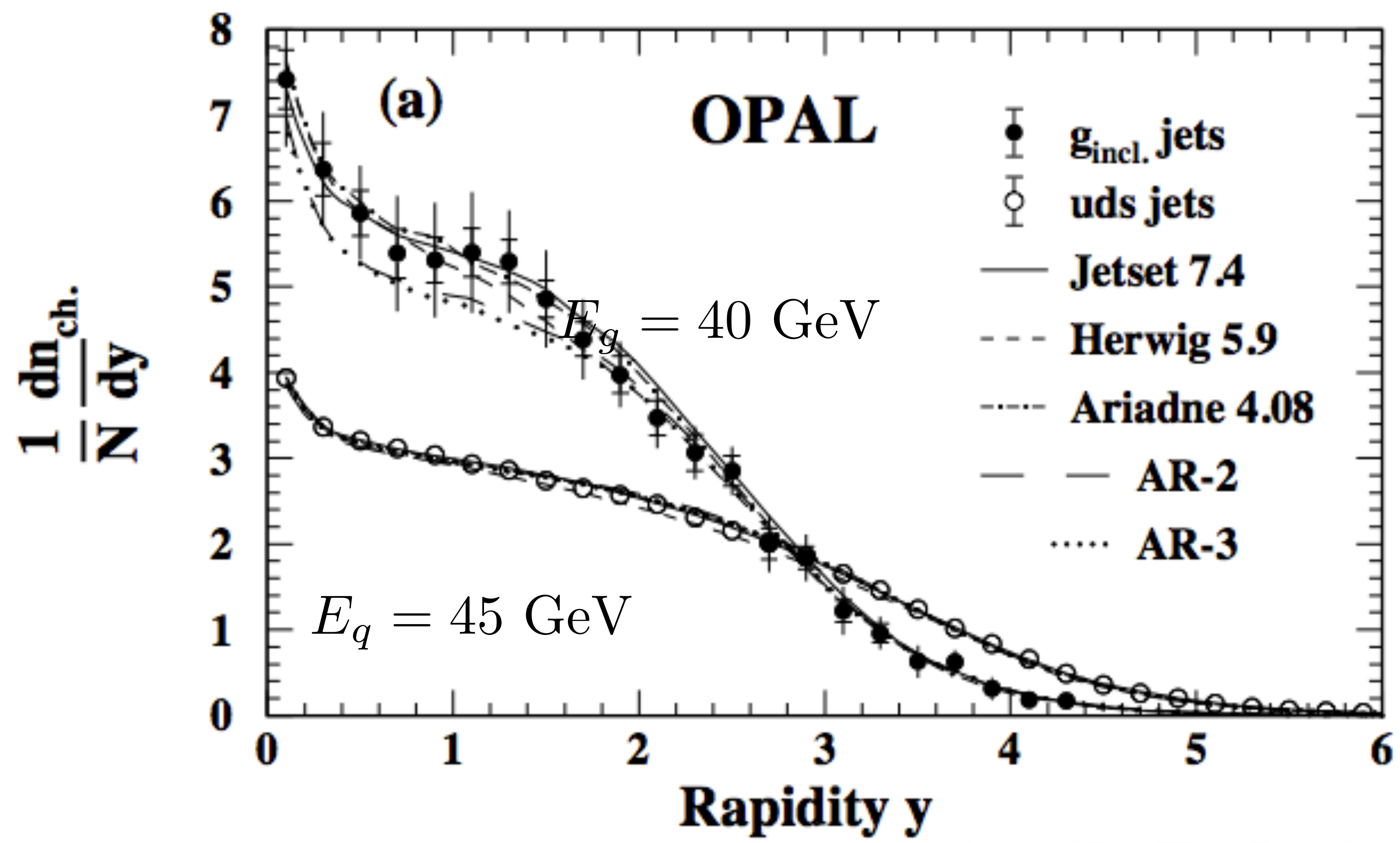
- Can we get a sample of H→gg pure enough for QCD studies?
- Requires good **H→gg vs H→bb**;
- Driven by Higgs studies requirements?

Z→bbg vs Z→qq(g) →

- g in one hemisphere recoils against b-jets in other hemisphere: **b tagging**

Study differential shape(s): N_{ch} (+low-R calo)

- (R ~ 0.1 also useful for jet substructure)



Scaling: radiative events → Forward Boosted

Scaling is **slow**, logarithmic → prefer large lever arm ← (Also useful for FFs & general scaling studies)

- $E_{CM} > E_{Belle}$ ~ 10 GeV **[~ 10 events / GeV at LEP];**
- Useful benchmarks could be E_{CM} ~ 10 (cross checks with Belle), 20, **30** (geom. mean between Belle and m_Z), 45 GeV (=m_Z/2) and 80 GeV = m_W

SUMMARY / OUTLOOK

QCD: (the only) **unbroken Yang-Mills theory that can be compared directly with experiment. Rich structure.**

CEPC / FCC-ee have tremendous potential to make decisive & detailed measurements.

End of era of testing $SU(3)_C$ → Precision determinations of α_s

Theory still evolving and new questions highlighted by LHC

Confinement is still hard

LEP precision finally exhausted, almost 20 years after shutdown.

Current generation of theory models show few (albeit some) discrepancies with LEP

Within next decade: expect significant perturbative advances and next-generation hadronisation models.

+ QCD in γγ collisions, interplay with EW, H, BSM, Precision Legacy for future pp collider