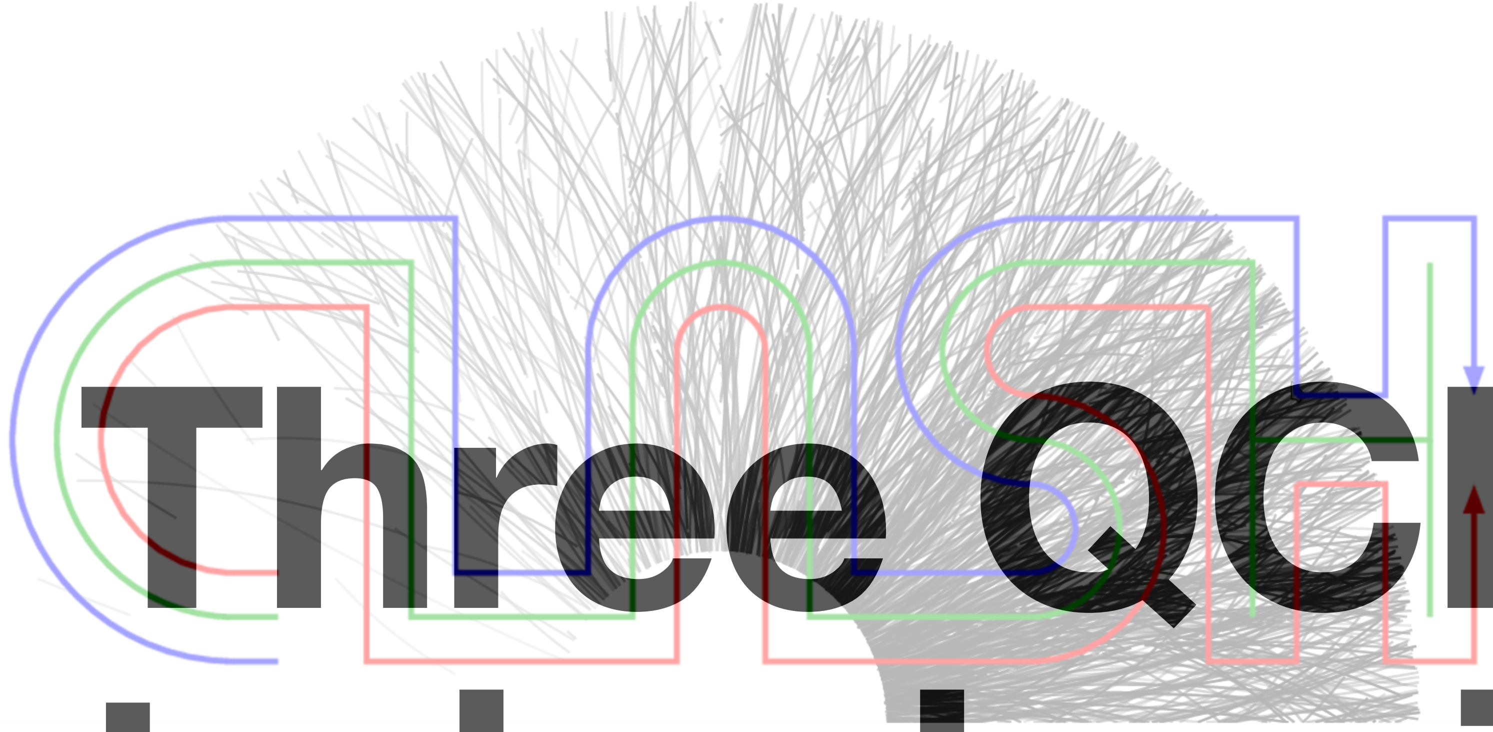


Three QCD challenges relating to hadronization

We would like to charge each speaker to share their thoughts on the hadronization problem, both for small and large collisions systems, based on their personal expertise and preferences.

Christian Bierlich, Münster, September 2024
QCD challenges from pp to AA
Contact:
christian.bierlich@fysik.lu.se
https://www.pythia.org/

LUNDS UNIVERSITET

Vetenskapsrådet

Lund strings: 1 slide overview

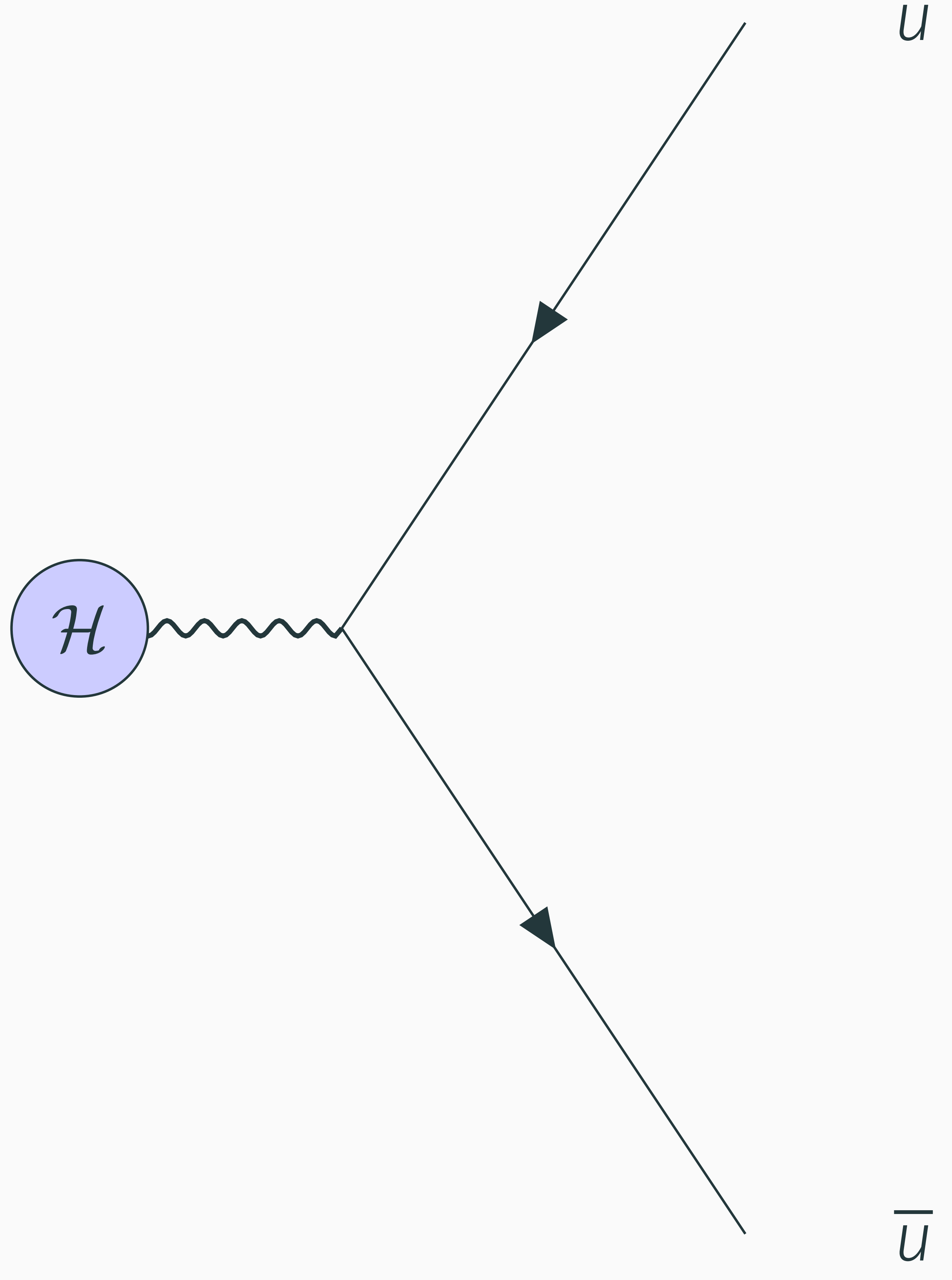
Many parameters:

- Kinematics: a, b, $\sigma_{p_\perp}$.
- Quark/diquark flavour selection: ρ, ξ, x, y.
- Hadron spin + η, η' suppression.
- Specialized models (baryons...).
- More for excited states, usually disabled.

Governing equations

Longitudinal kinematics: $f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$

Flavour and $p_\perp$: $\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}^2 p_\perp} \propto \exp\left(-\pi m_{\perp,q}^2/\kappa\right)$



Simple system, eg. Z-boson to quark-anti-quark

Three topics

1. Reweightable hadronization — a new tool that may help experiments asking more pointed questions of models. At least our model. 2308.13459, 2410.XXXXX.

2. Discriminating observables — is it possible to conclusively determine whether strangeness enhancement in pp is due to QGP or not? The answer is maybe. arXiv:2403.00511.

3. Charm baryons and CR — are charm baryons rinse and repeat from strange sector? What do we learn by pitting them against each other? Is this where we pA will prove most useful? arXiv:2309.12452.

Part 1: Reweighting hadronization

The string break algorithm

Basically unchanged since the 1980's

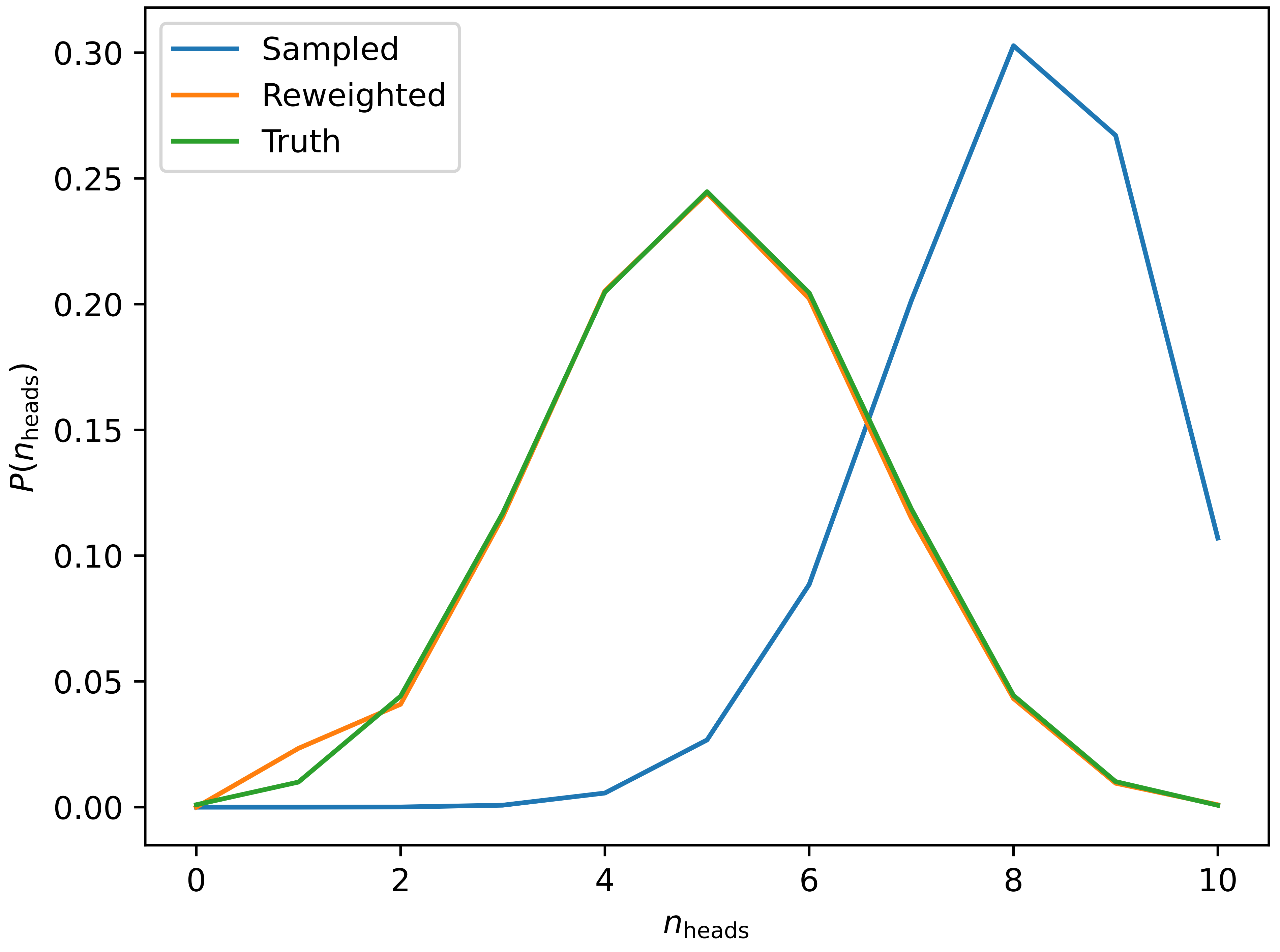
- `for` each string:
    1. Select randomly one end or the other.
    2. Pick the hadron flavour.
        - 2.1 Pick string break flavour.
        - 2.2 Force suppression according to **SU(6)** CG.
        - 2.3 Possibly **`break`**.
    3. Pick transverse momentum.
    4. Pick *z* and construct full hadron momentum.
    5. If energy/momentum used up, **`break`**.
- Result: Output which looks like measured "events".
- Unit weights means interpretation as single event.

Reweighting: A pedagogical example

Simulate a fair coin with a weighted coin

Sample statistics on “heads” state. Throw away half the statistics?

Let P(“heads”) = 0.8, and reweighs at the level of the observable



Algorithmic reweighing (2308.13459)

If your state is selected by accept/reject with no analytic PDF

- Sample z from $f(z)$. Continuous distribution, standard Accept/Reject algorithm. $f_{\mathrm{reject}} = 1 - f_{\mathrm{accept}}$ (unitarity).

$$f_{\mathrm{accept}}(z, c_i) \equiv \frac{f(z, c_i)}{f_{\mathrm{max}}(c_i)} \leq 1; z_{\mathrm{trial}} \leftarrow R_1; \text{accept iff } f_{\mathrm{accept}}(z_{\mathrm{trial}}) > R_2.$$

- Now $c_i \mapsto c_i'$. Generate with c_i, weight maps to alternative.

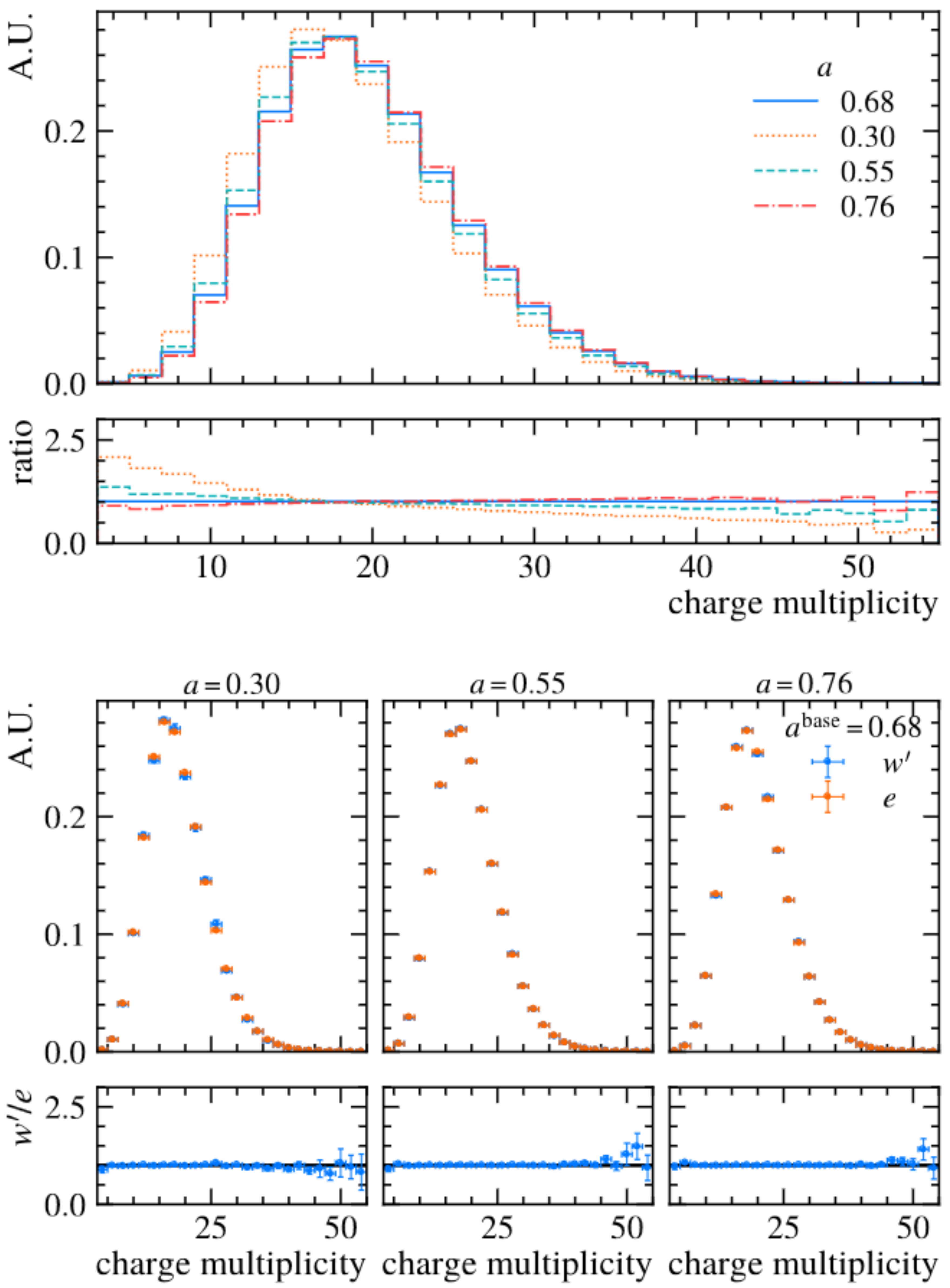
$$w = \prod_{j \in \mathrm{accepted}} \frac{f(z_j, c_i')}{f(z_j, c_i)} \prod_{k \in \mathrm{rejected}} \frac{f_{\mathrm{max}}(c_i) - f(z_k, c_i')}{f_{\mathrm{max}}(c_i') - f(z_k, c_i)}$$

- Standard technique for PS variations.
- Reweighting $p_\perp$ analytically.
- Result: reweight to alternate reality c_i, even after detector simulation. Note c_i' must be selected *a priori*.

Sample results

More in paper (2308.13459)

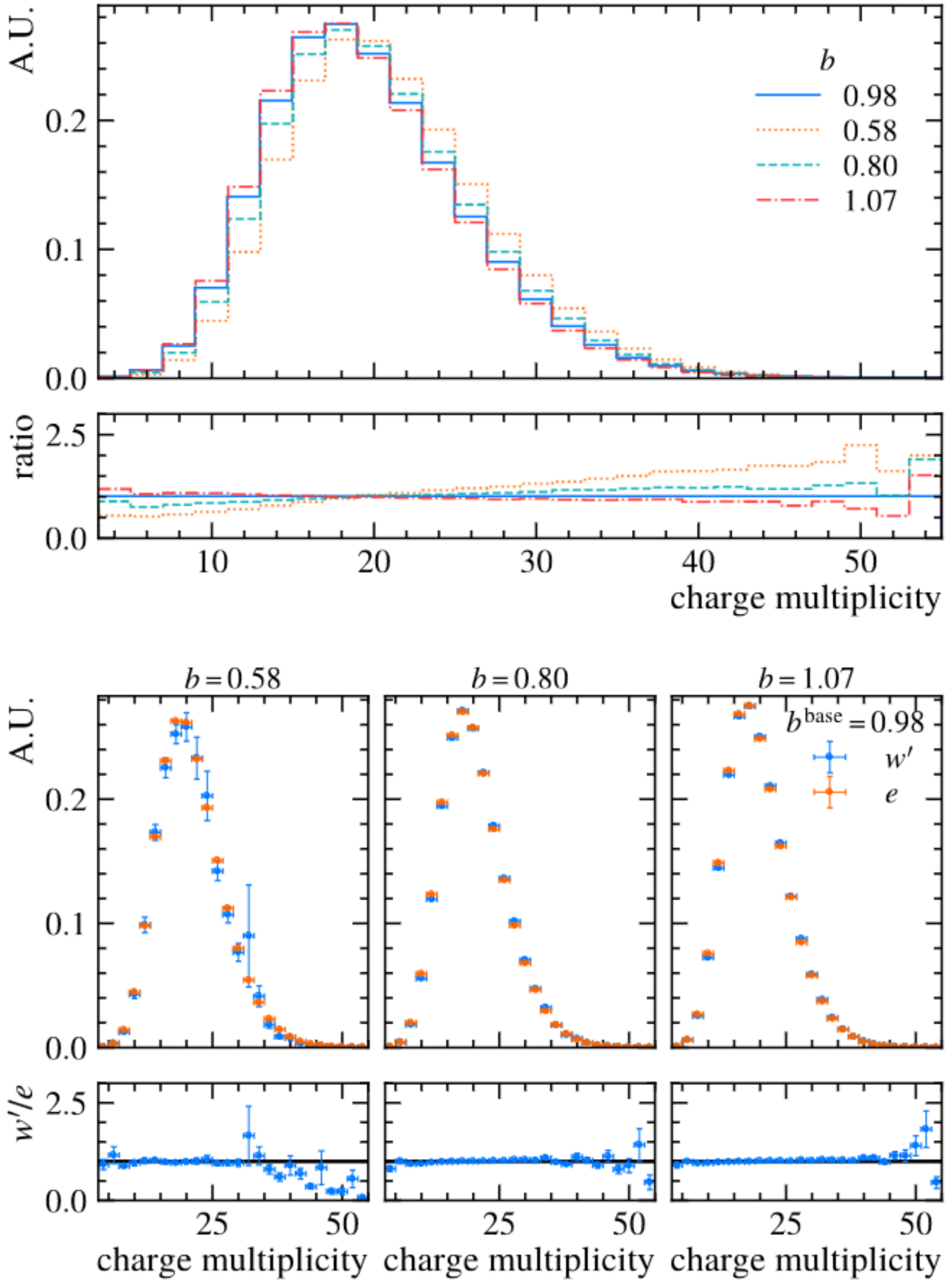
- Charged multiplicity, different values of *a.*
- Top: Truth distribution, effect on charged multiplicity (e^+e^-).
- Bottom: *e*-curves explicitly generated with *a'*, *w'*-curves reweighted from base *a* to *a'.*



Sample results

More in paper (2308.13459)

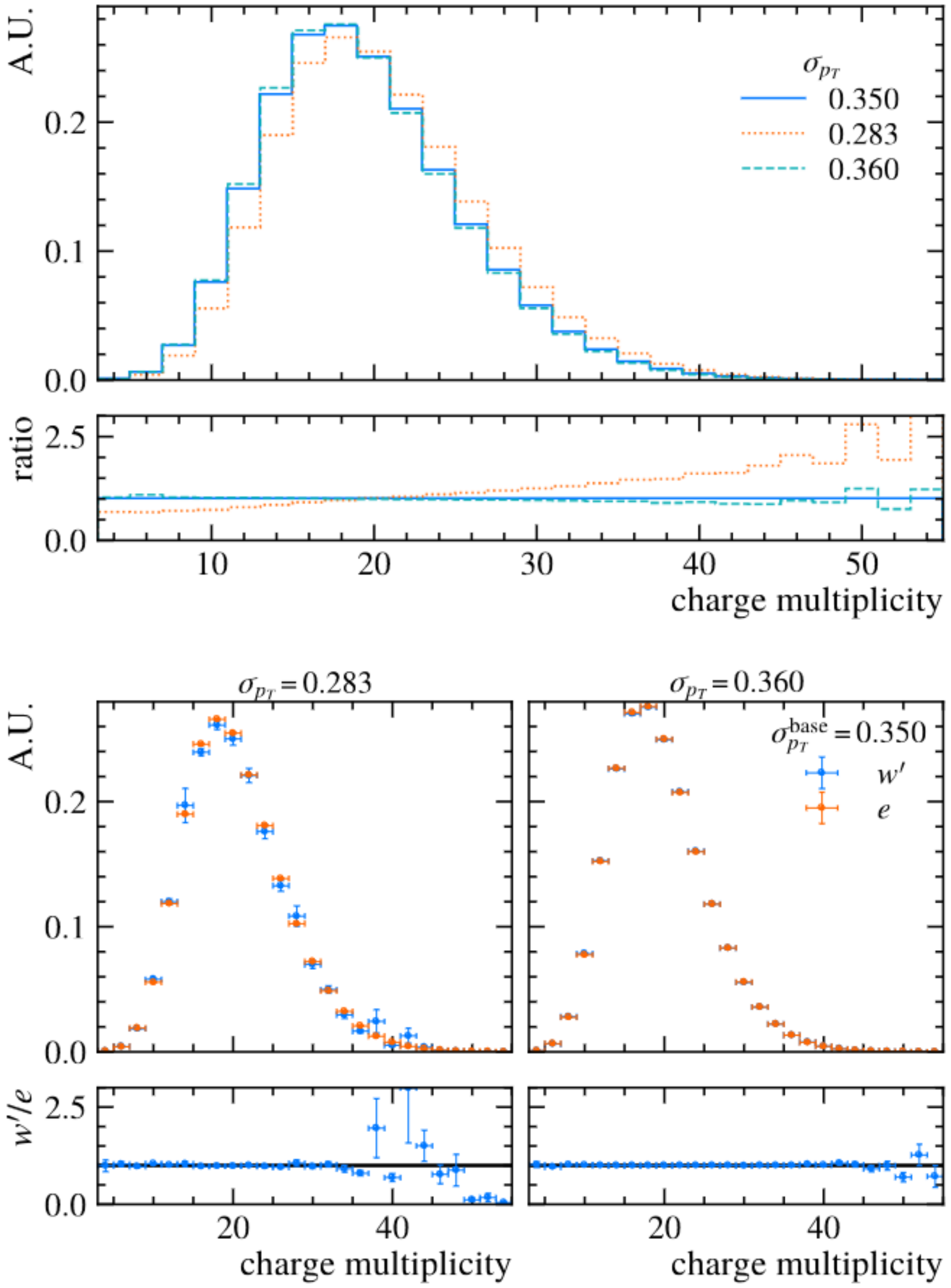
- Charged multiplicity, different values of *b.*
- Top: Truth distribution, effect on charged multiplicity (e^+e^-).
- Bottom: *e*-curves explicitly generated with *b'*, *w'*-curves reweighted from base *b* to *b'*.



Sample results

More in paper (2308.13459)

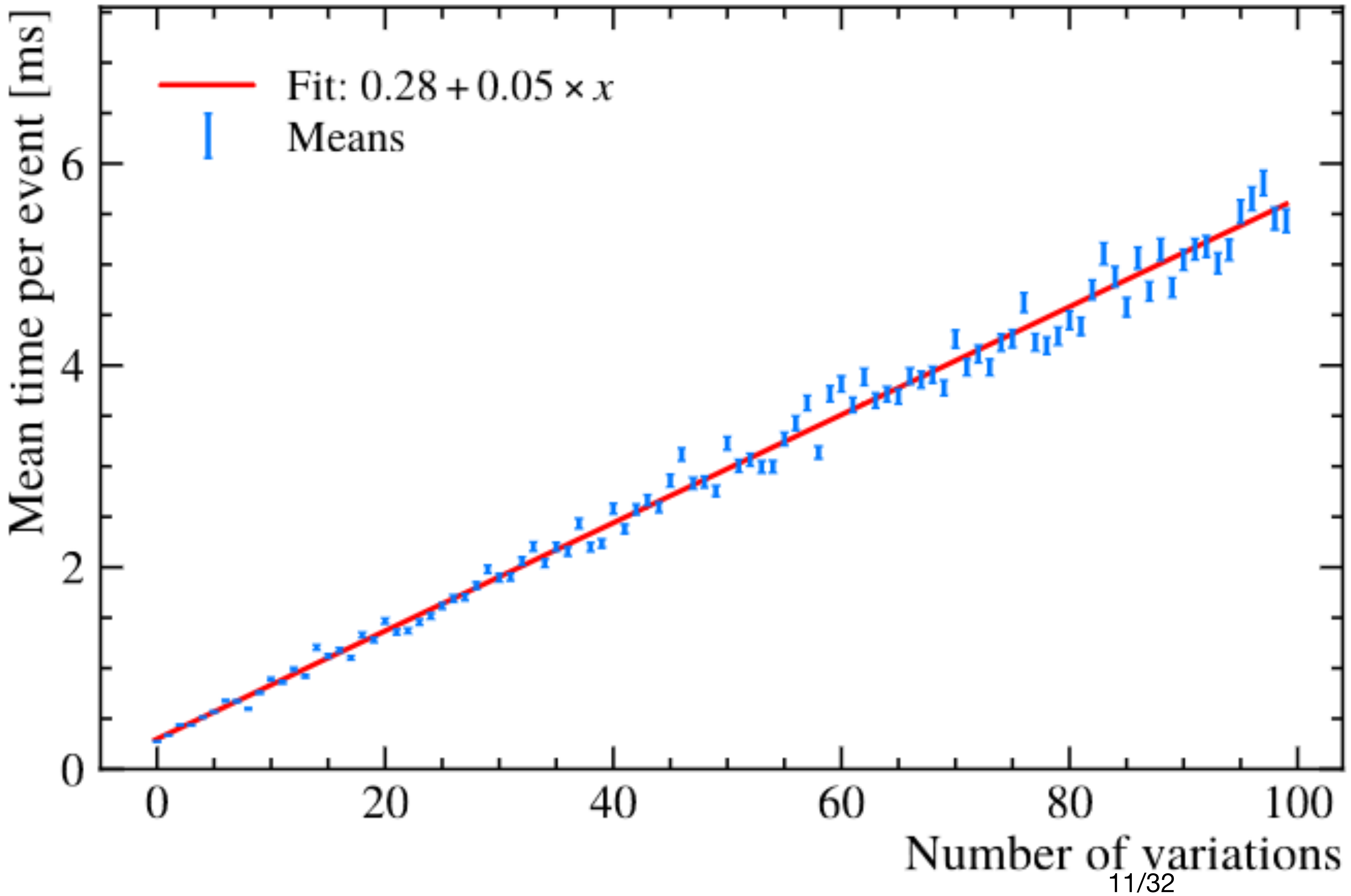
- Charged multiplicity, different values of $\sigma_{p_\perp}$.
- Top: Truth distribution, effect on charged multiplicity (e^+e^-).
- Bottom: *e*-curves explicitly generated with $\sigma'_{p_\perp}$, *w'*-curves reweighted from base $\sigma_{p_\perp}$ to $\sigma'_{p_\perp}$.

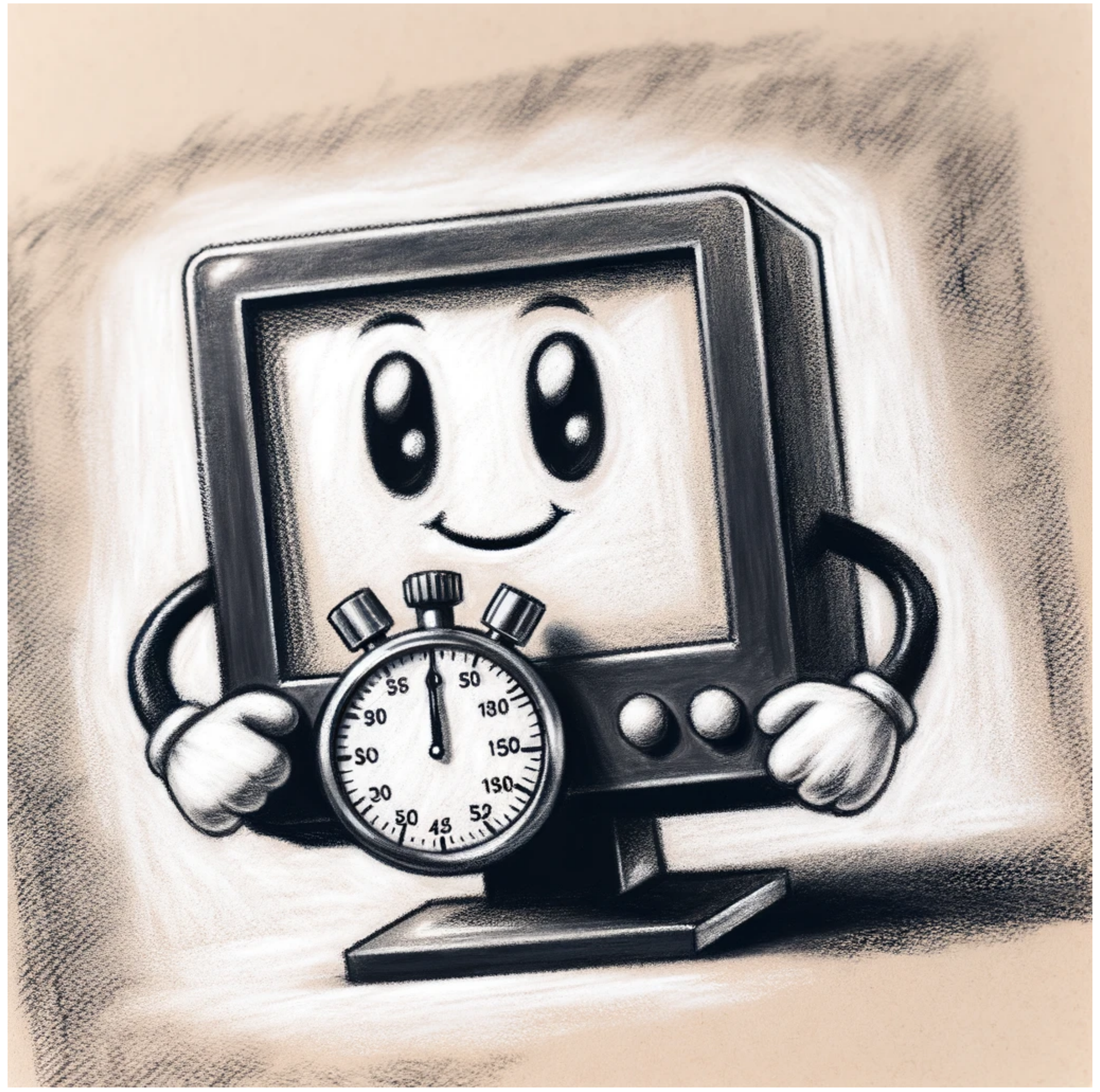


Timing

Drastic improvements for large number of variations

- This is exactly what you need for data driven error estimation.
- Normal procedure: Rerun every variation explicitly.





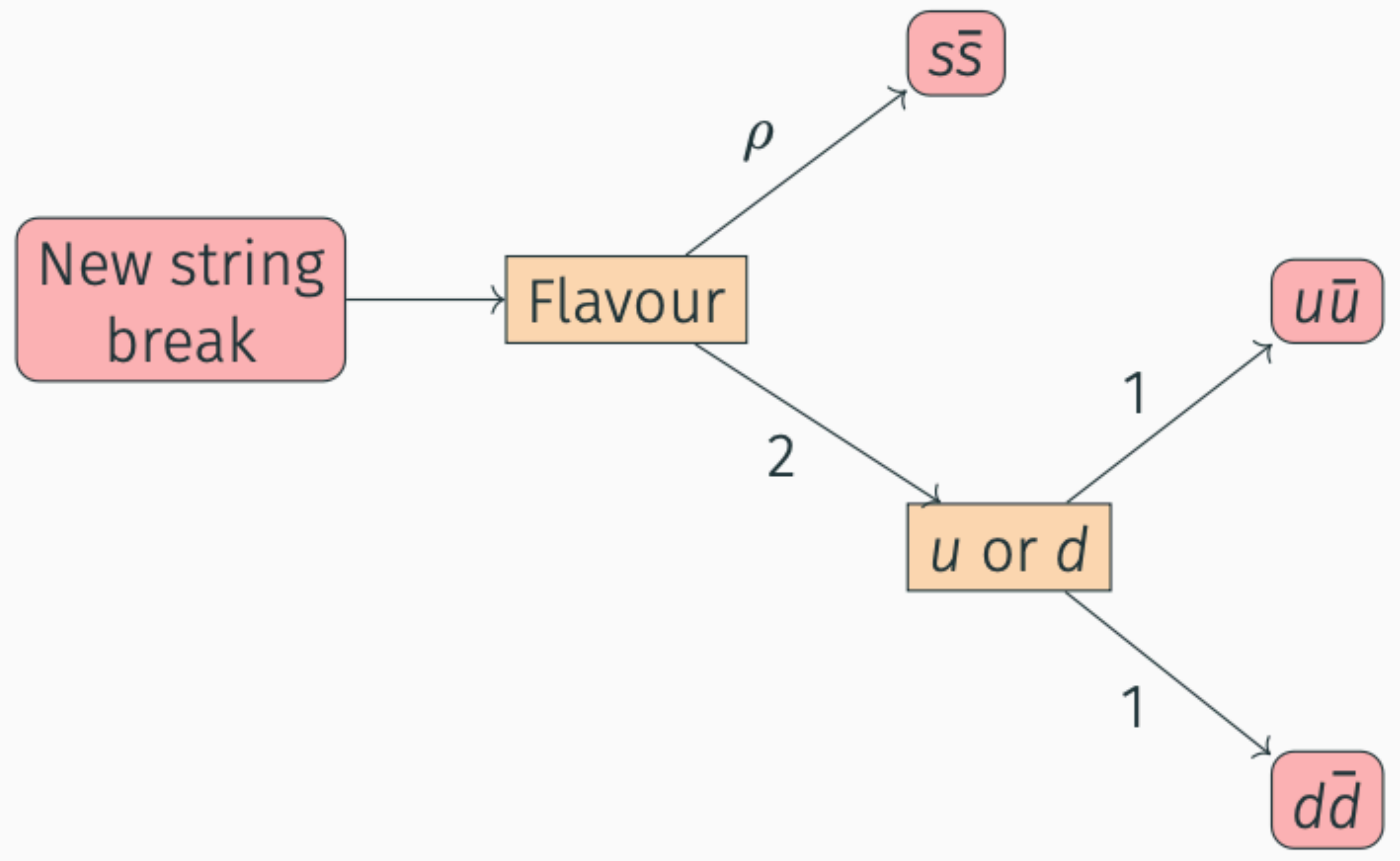
Flavour reweigthing (in pipeline)

More like heads/tails

- Sample **discrete flavour break**, reweight to alternate reality with different parameters. Or the other way around!

- Weight calculable from string break history, which can be accessed.

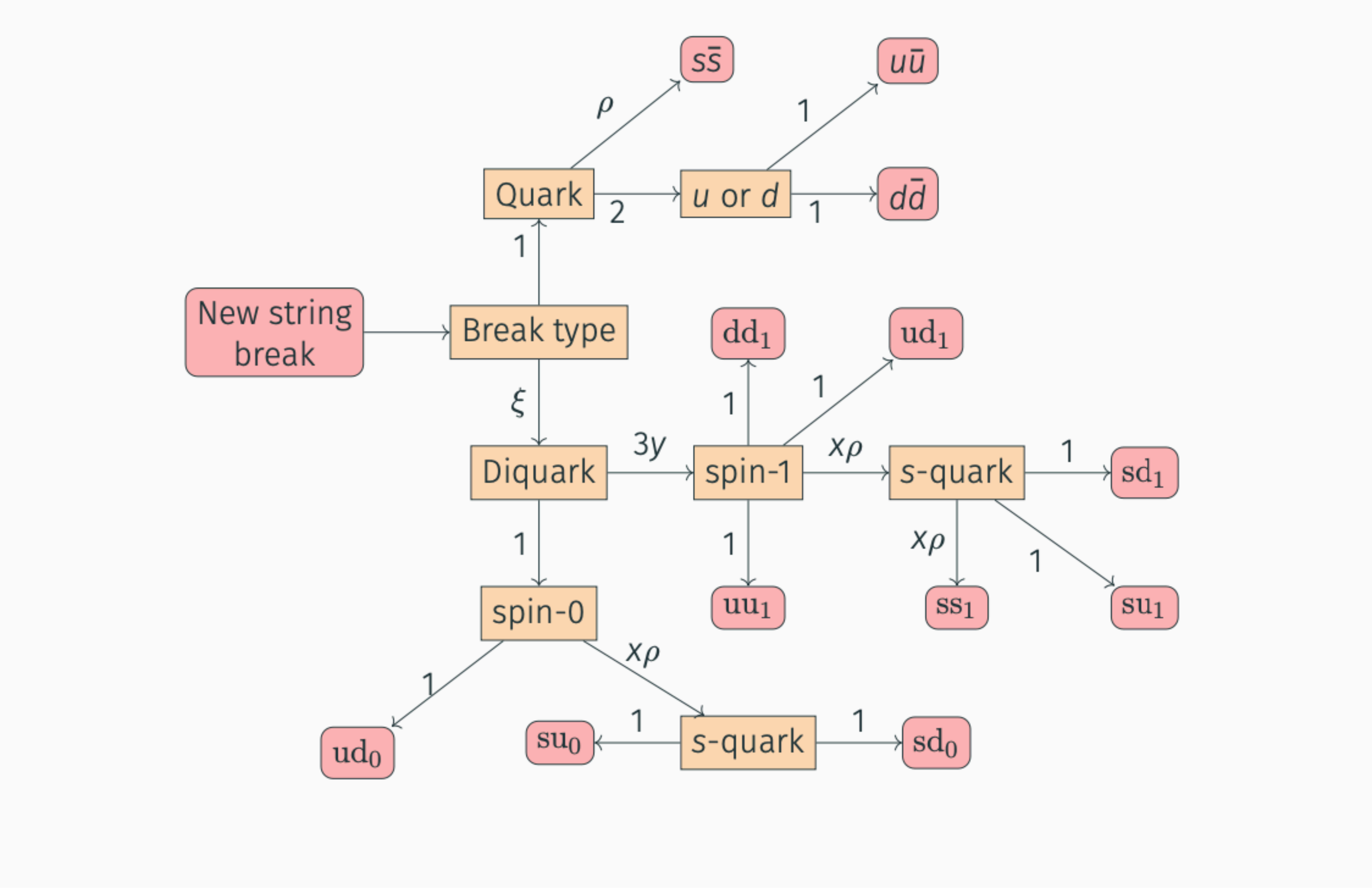
$$\mathcal{P}_{ns}(\rho) = \binom{N}{n} p^n (1-p)^{N-n} \Rightarrow w = \left(\frac{p}{p'}\right)^n (1-p')^{n-N} (1-p)^{N-n}$$



Baryons are complicated!

Only simple baryon model for now

- Further accept/reject step, **SU(6)** spin × flavor Clebsch-Gordans.



Baryons are complicated!

Only simple baryon model for now

- Further accept/reject step, **SU(6)** spin × flavor Clebsch-Gordans.

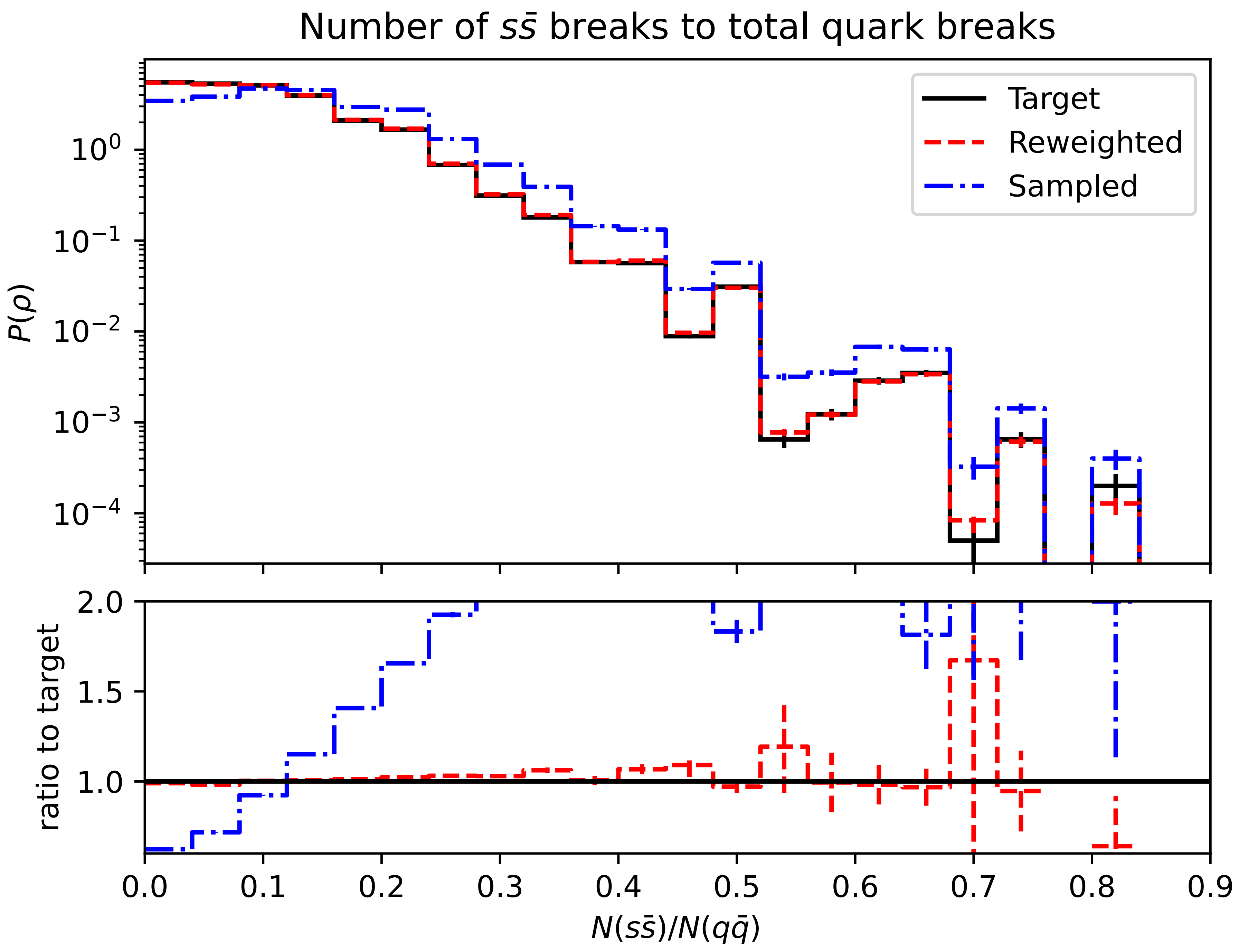
$$
\begin{aligned}
w = &\underbrace{\left(\frac{p_D}{p'_D}\right)^{n_{Q\bar{Q}}} (1-p'_D)^{n_{Q\bar{Q}}-n}(1-p_D)^{n-n_{Q\bar{Q}}}}_{Q\bar{Q}\text{ breaks from all breaks}} \times \underbrace{\left(\frac{p_s}{p'_s}\right)^{n_{s\bar{s}}} (1-p'_s)^{n_{s\bar{s}}-n_{q\bar{q}}}(1-p_s)^{n_{q\bar{q}}-n_{s\bar{s}}}}_{s\bar{s}\text{ from }q\bar{q}\text{ breaks}} \times \\
&\times \underbrace{\left(\frac{p_Y}{p'_Y}\right)^{n_{QQ_1}} (1-p'_Y)^{n_{QQ_1}-n_{QQ}}(1-p_Y)^{n_{QQ}-n_{QQ_1}}}_{QQ_1\text{ breaks from all }Q\bar{Q}\text{ breaks}} \times \\
&\times \underbrace{\left(\frac{p_{X_0}}{p'_{X_0}}\right)^{n_{QQ_{s0}}} (1-p'_{X_0})^{n_{QQ_{s0}}-n_{QQ_0}}(1-p_{X_0})^{n_{QQ_0}-n_{QQ_{s0}}}}_{QQ_{s0}\text{ breaks from all }QQ_0\text{ breaks}} \times \\
&\times \underbrace{\left(\frac{p_{X_1}}{p'_{X_1}}\right)^{n_{QQ_{s1}}} (1-p'_{X_1})^{n_{QQ_{s1}}-n_{QQ_1}}(1-p_{X_1})^{n_{QQ_1}-n_{QQ_{s1}}}}_{QQ_{s1}\text{ breaks from all }QQ_1\text{ breaks}} \times \\
&\times \underbrace{\left(\frac{p_{XX_1}}{p'_{XX_1}}\right)^{n_{ss_1}} (1-p'_{XX_1})^{n_{ss_1}-n_{QQ_{s1}}}(1-p_{XX_1})^{n_{QQ_{s1}}-n_{ss_1}}}_{ss_1\text{ breaks from all }QQ_{s1}\text{ breaks}},
\end{aligned}
\tag{6}
$$

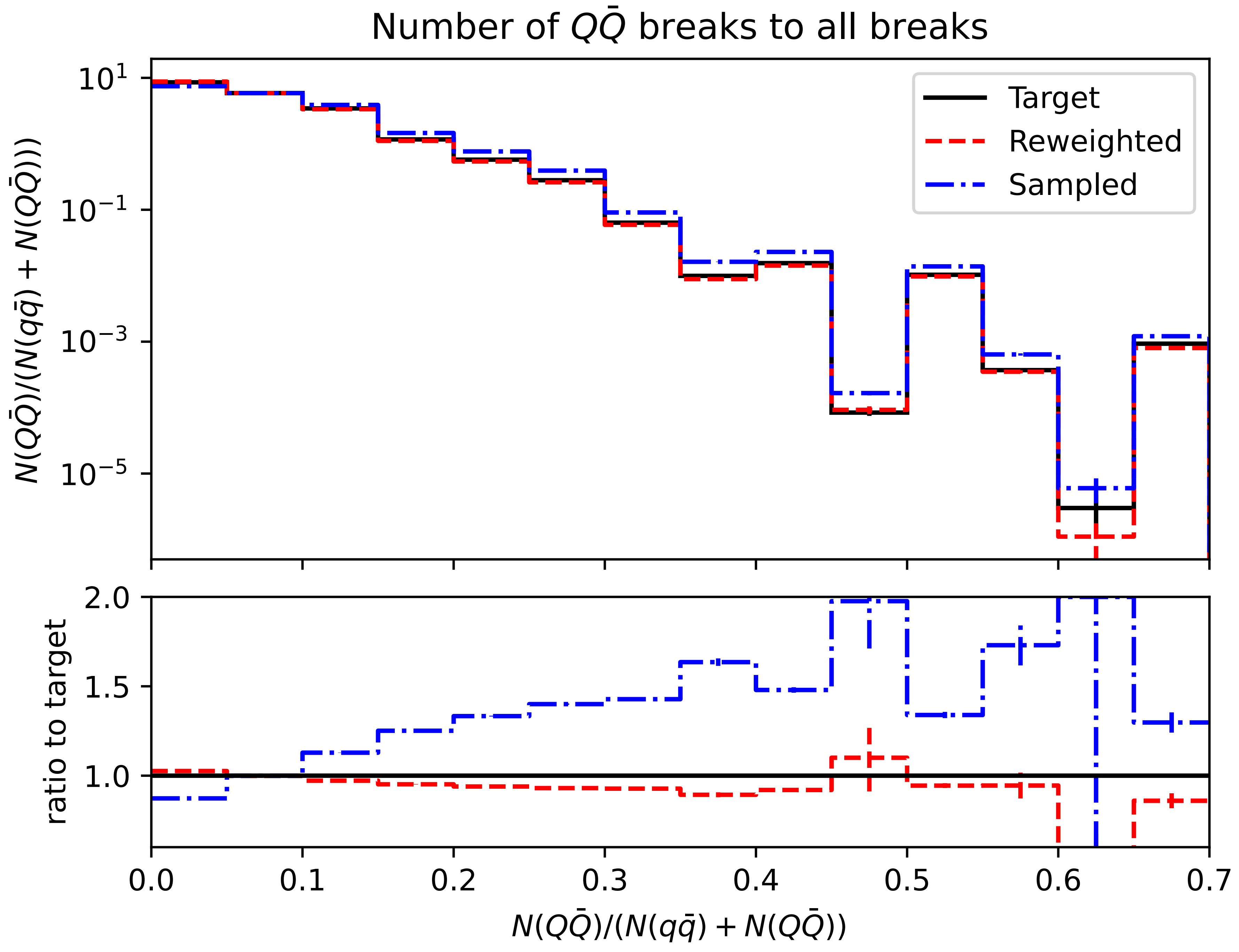
$$
\begin{aligned}
p_D &= \frac{\xi}{1+\xi} && \text{(diquark break from any string break)},\\
p_s &= \frac{\rho}{2+\rho} && (s\bar{s}\text{ break from any }q\bar{q}\text{ break}),\\
p_Y &= \frac{3y(3+x\rho(2+x\rho))}{1+2x\rho+3y(3+x\rho(2+x\rho))} && (QQ_1\text{ break from any }Q\bar{Q}\text{ break}),\\
p_{X_0} &= \frac{2x\rho}{1+2x\rho} && (QQ_{s0}\text{ break from any }QQ_0\text{ break}),\\
p_{X_1} &= \frac{x\rho}{1+x\rho} && (QQ_{s1}\text{ break from any }QQ_1\text{ break}),\\
p_{XX_1} &= \frac{x\rho}{2+x\rho} && (ss_1\text{ break from any }QQ_{s1}\text{ break}).
\end{aligned}
$$

Flavour reweighing

Sample results

- **Take home:** Generate your rare final state in alternate reality where it is common. Reweight back to real world.
- Essential for establishing theory uncertainties. Bonus: *post hoc* procedure doable after detector simulation.



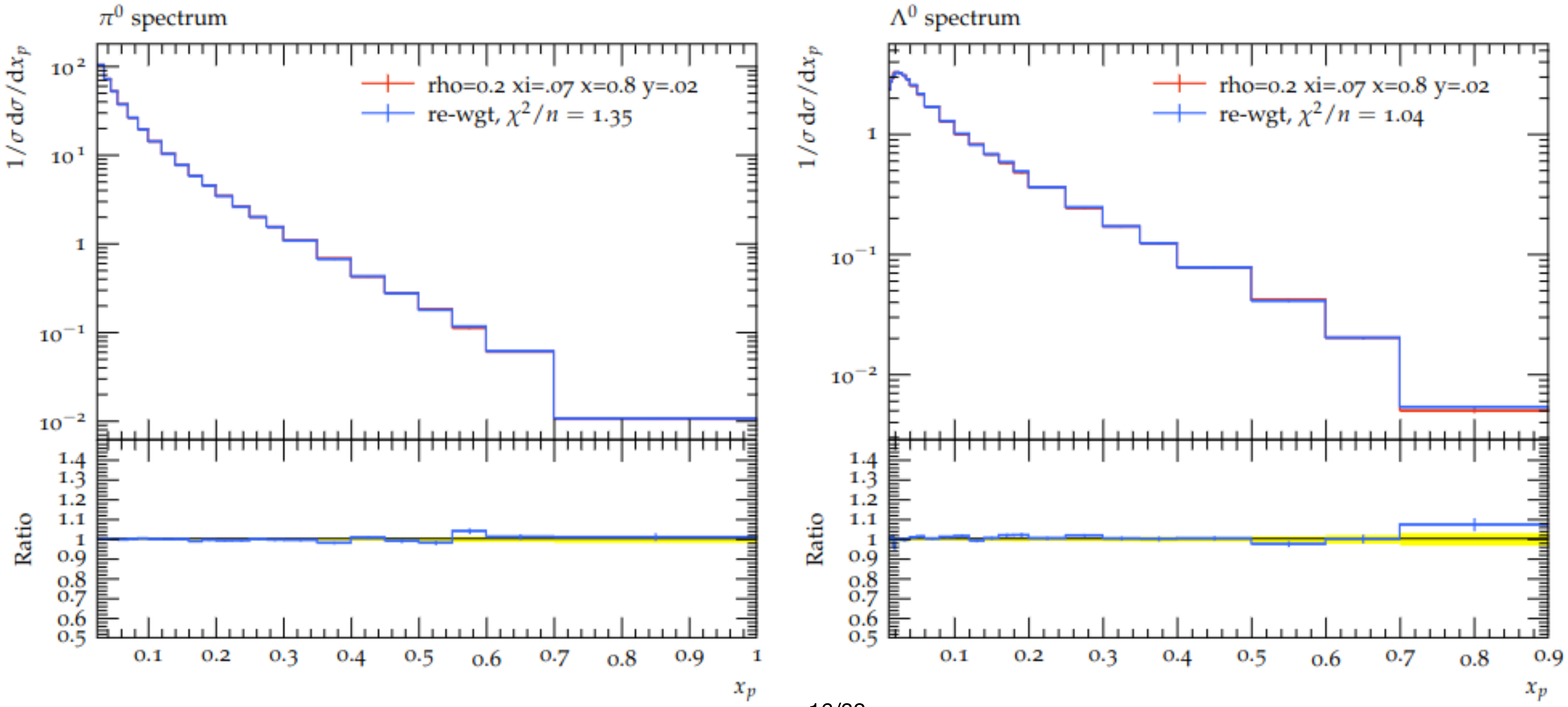


Flavour reweighing

Sample results

- **Take home:** Generate your rare final state in alternate reality where it is common. Reweight back to real world.

- Think about the probability of producing some (full) state X given a model. Inverse problem? Given a state (data) X, which initial states does it correspond to? Livio's presentation?



How does this help us with challenges?

- **New tool:** Drastically reducing runtime enables new analyses (?).
    - On-the-fly tuning of new models -> exclusion?
    - Theory uncertainties. (Also after detector simulation)
    - Practical: theory trigger on rare final states. Useful for things other than compute times?
    - Event-by-event analysis (Bayes) with invertible model (not yet)
        - “Here is a data event. Which initial states correspond to this? With which probability?**”**
- **New tools allows asking new questions. What are the good questions to ask with this one?**

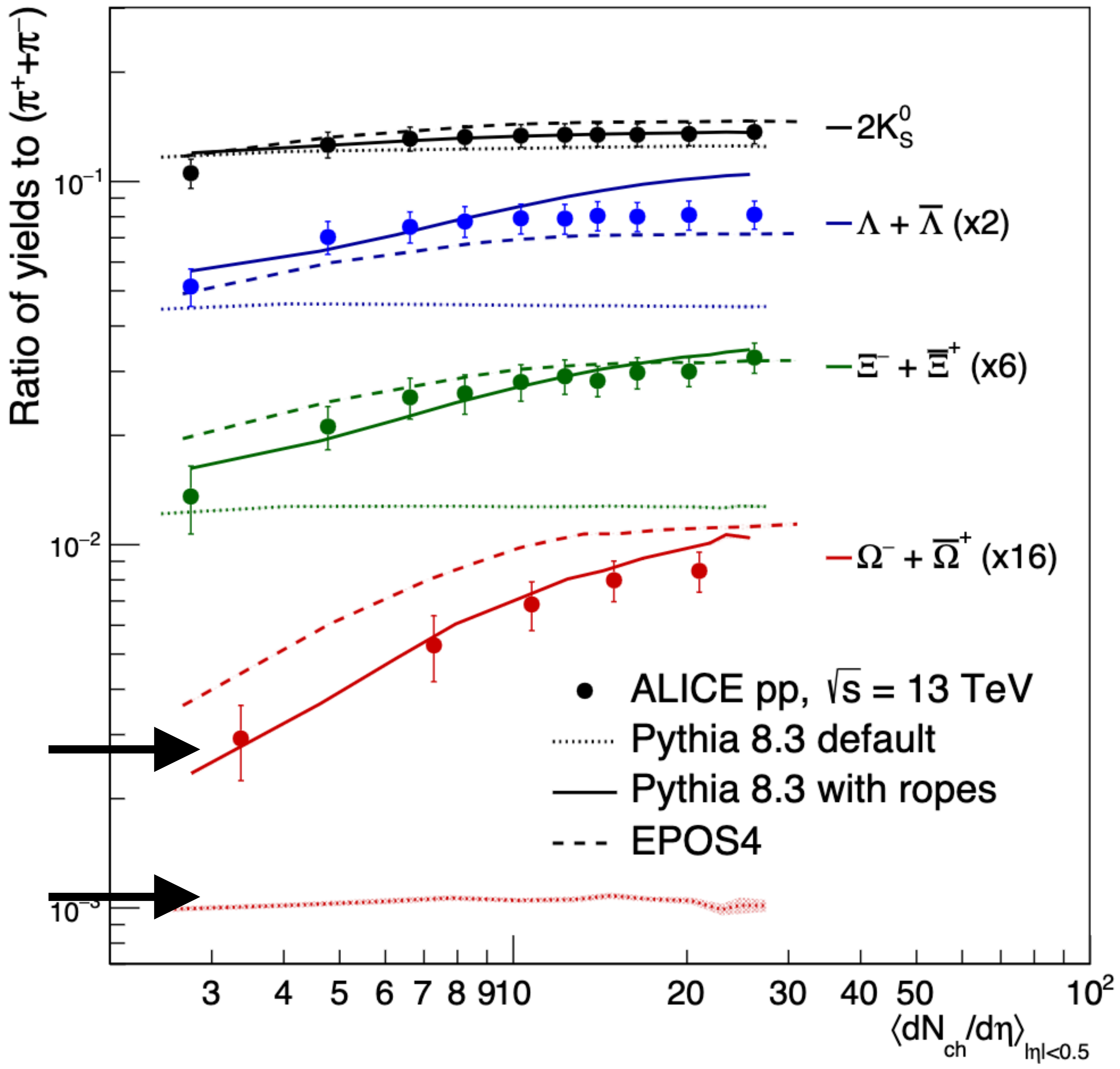
Part 2: Discriminating observables

Establish observables to discriminate

With S. Cannito and V. Zaccolo (Trieste), (2403.00511)

- How can we discriminate between these types of models?
- We need to ask the models for special features!

Observables must:
1. Be based on genuine model differences!
2. Produce deviations seen by eye!



Model differences

EPOS vs. PYTHIA proxies for QGP vs. no QGP

EPOS 4:

Microcanonical hadronization. Strangeness conservation over full volume.

The “core” is QGP, the “corona” is vacuum

$$\Omega(\{h_1, ..., h_n\}) = \frac{V^n}{(2\pi)^{3n}} \prod_{i=1}^{n} g_i \prod_{\alpha \in S} \frac{1}{n_\alpha!} \int \prod_{i=1}^{n} d^3p_i \delta\left(E - \sum \varepsilon_i\right) \delta\left(\sum \vec{p}_i\right) \delta_{Q,\sum q_i}$$

PYTHIA strings:

Strings always remain, hadrons produced in breaks.

Strangeness conservation in string breaks.

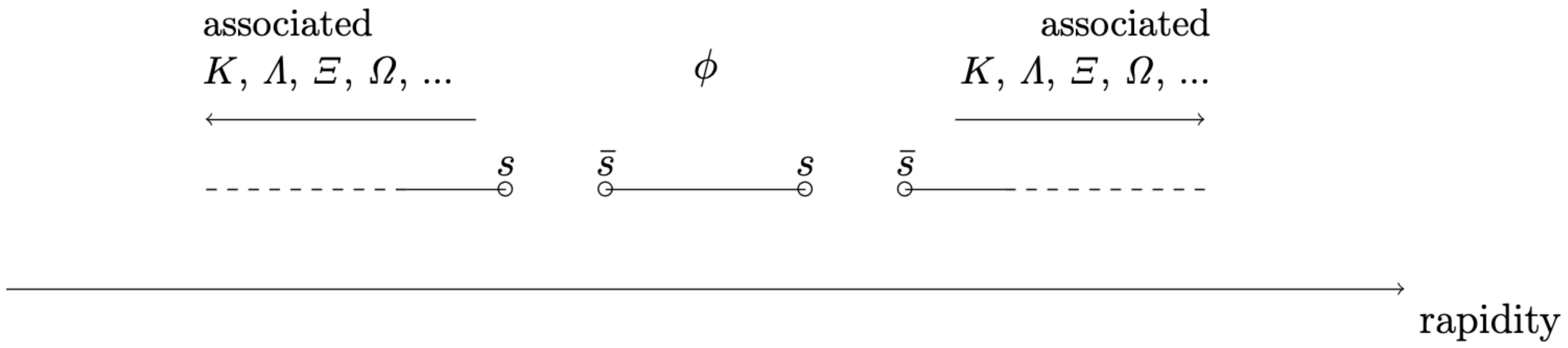
Strangeness enhancement by coherence.

$$\rho = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right)$$

The special role of the ϕ-meson

And using it as a trigger

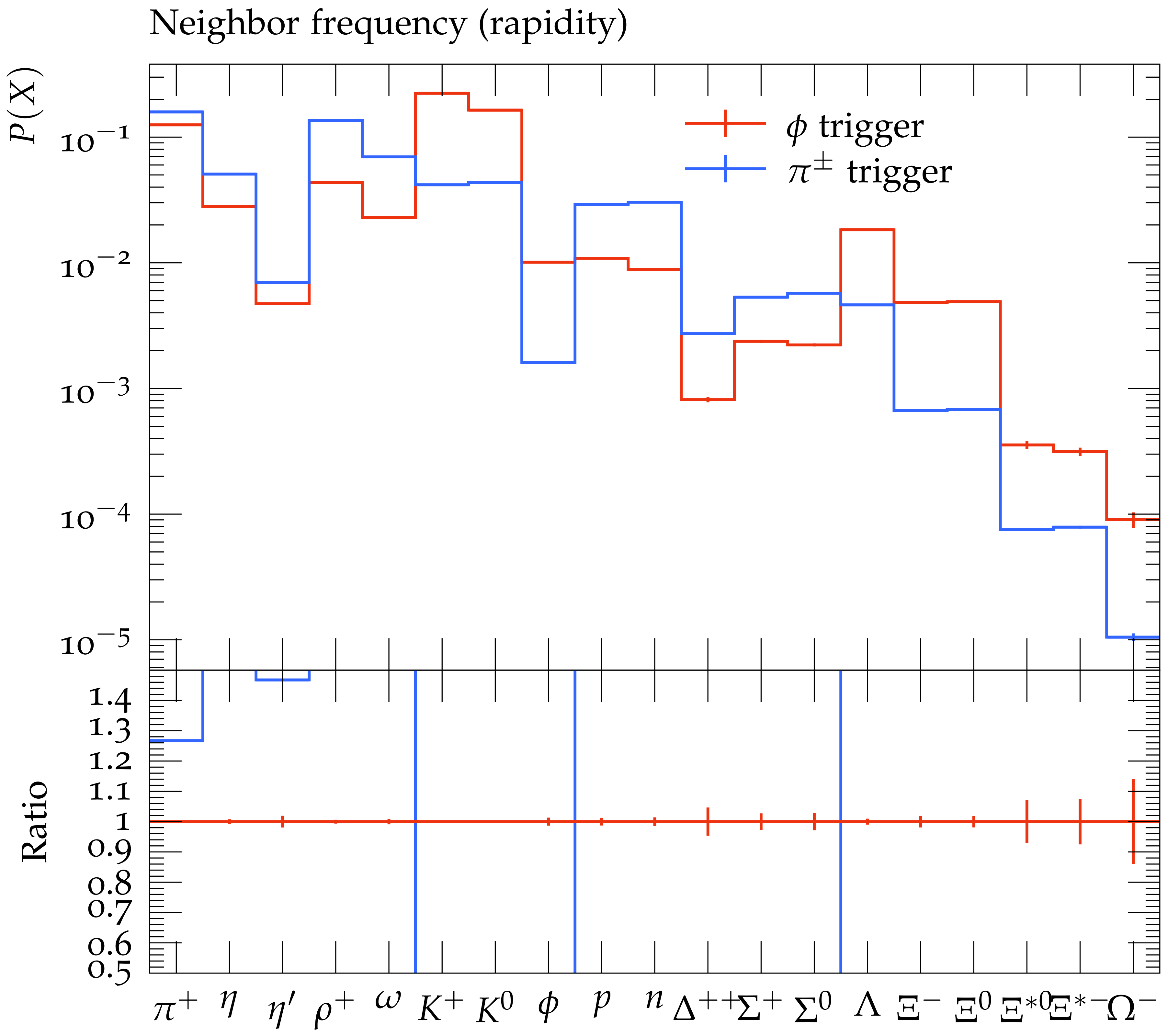
When a ϕ is produced, leftover strangeness is dangling.

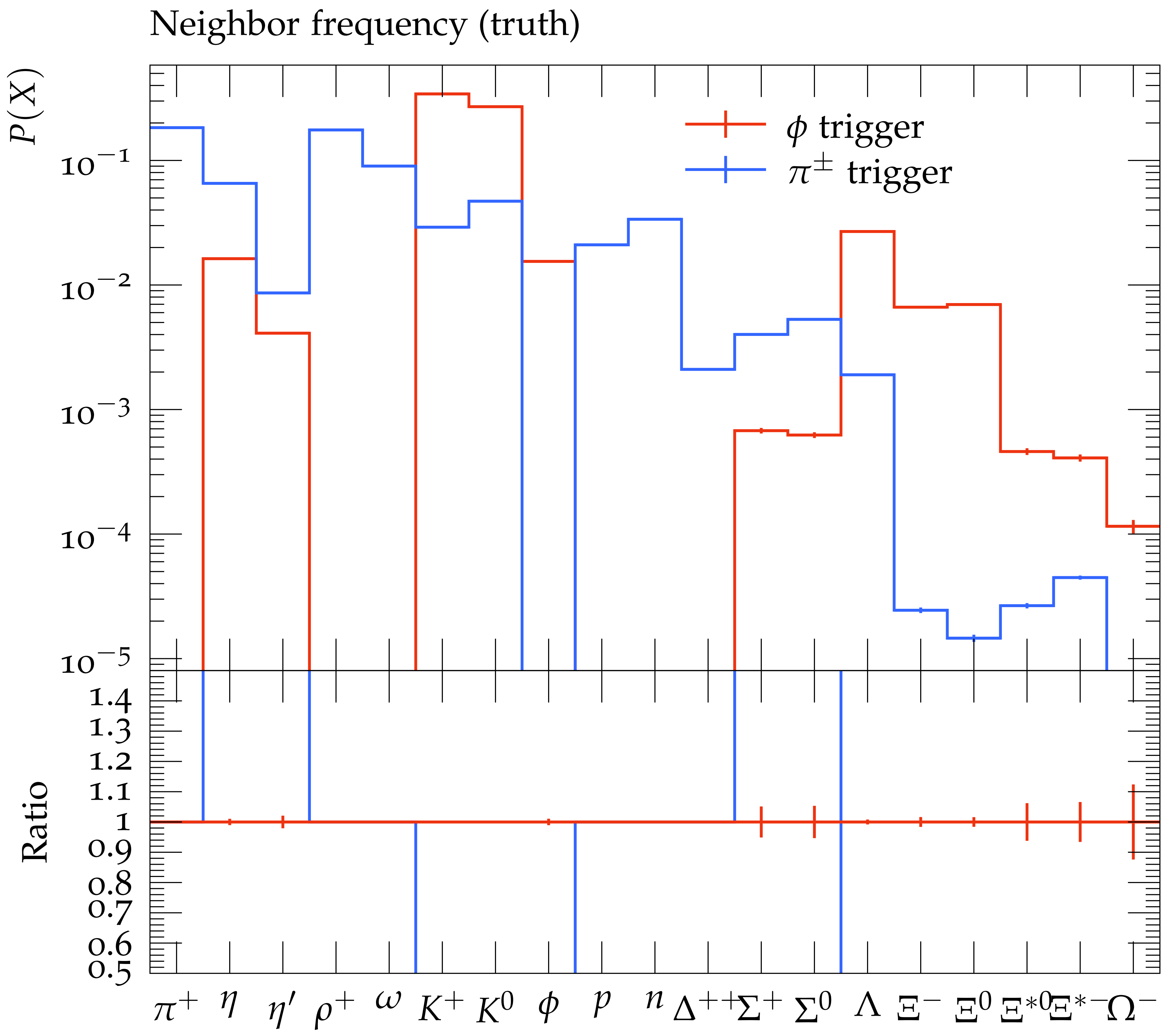


Neighbors will include the dangling strangeness!

Who is your neighbor?

Leaving aside small vector meson mixing

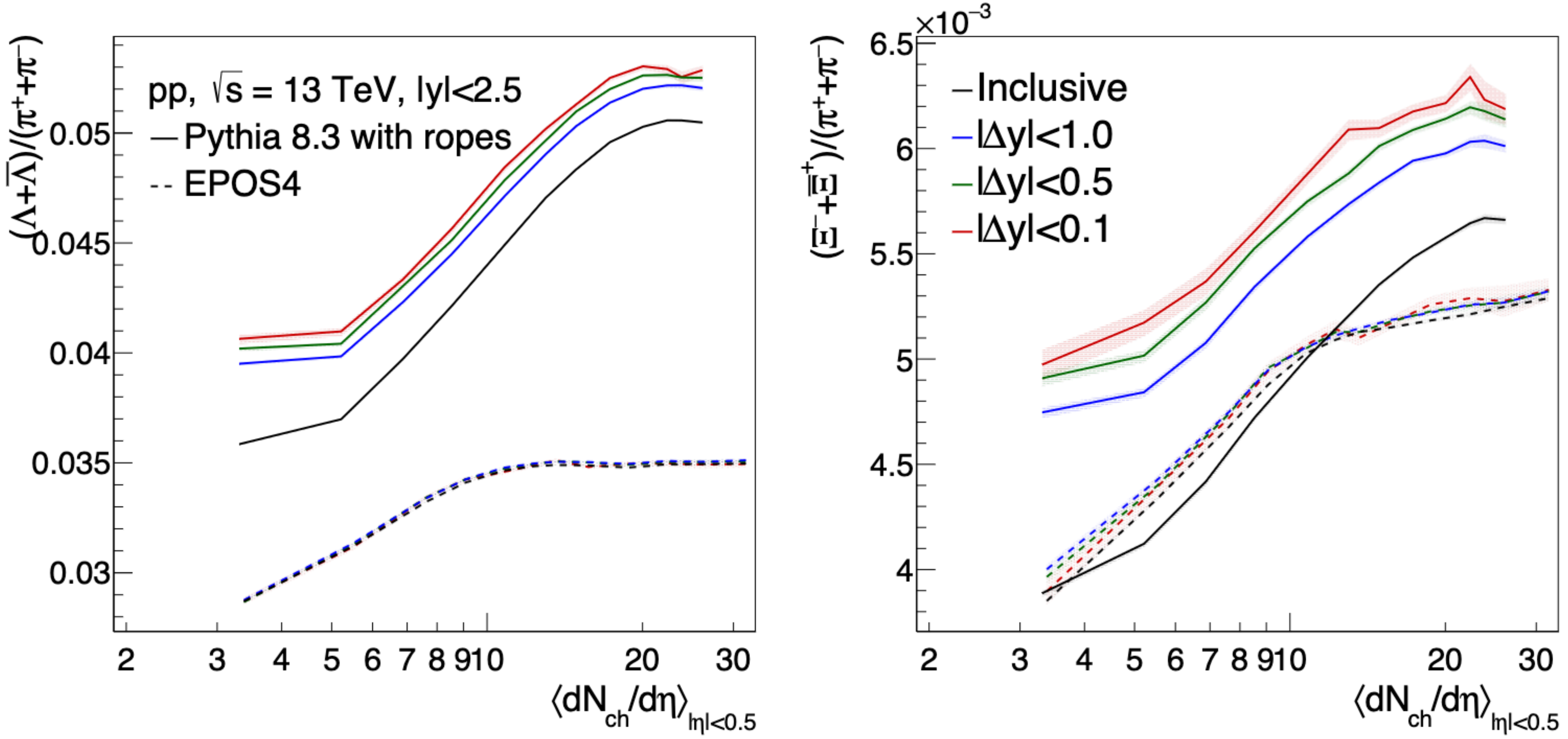




Must-see effect with string degrees of freedom!

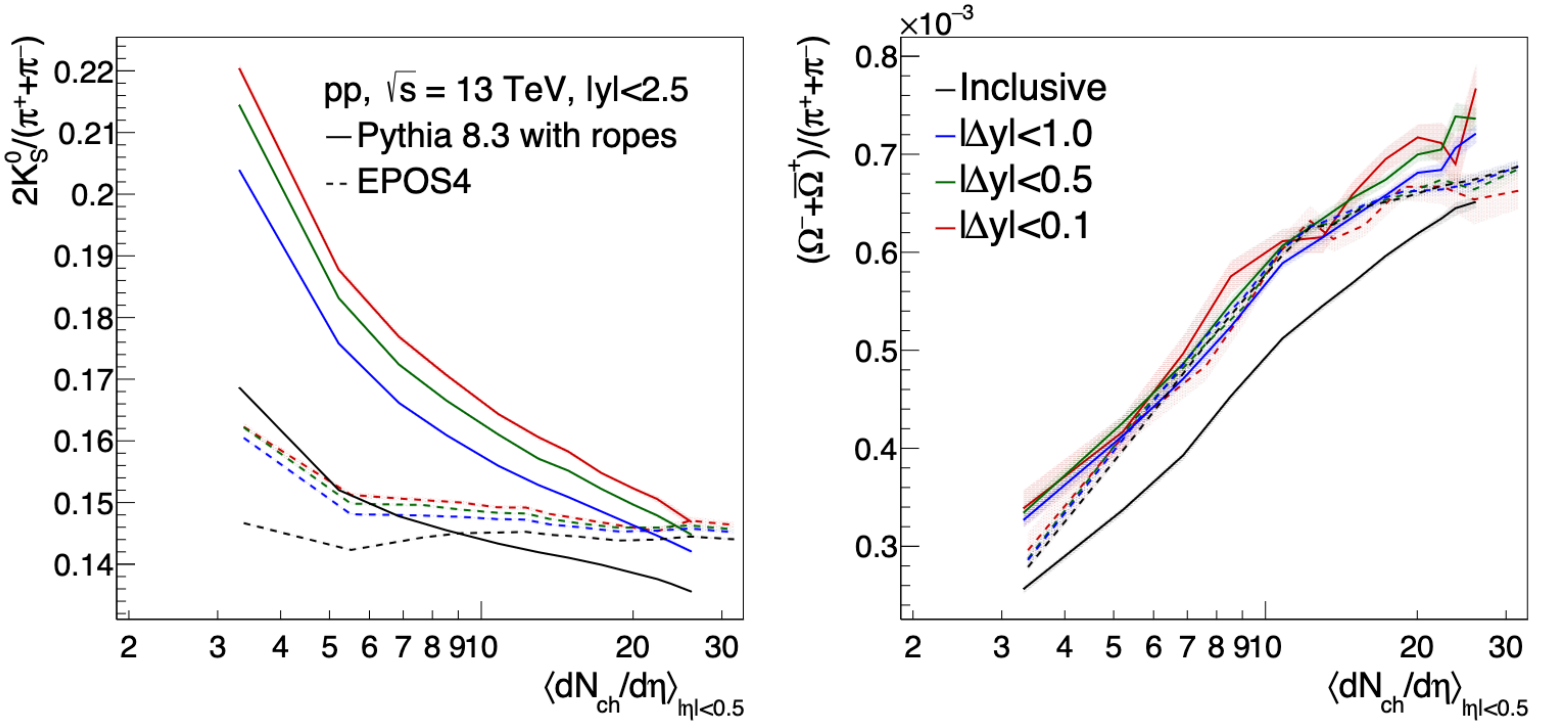
Triggered particle ratios

Large deviations — Qualitative, cannot be “tuned away”



Interesting corner cases

To be studied more! Could be more to learn with more flavour triggers



Questions

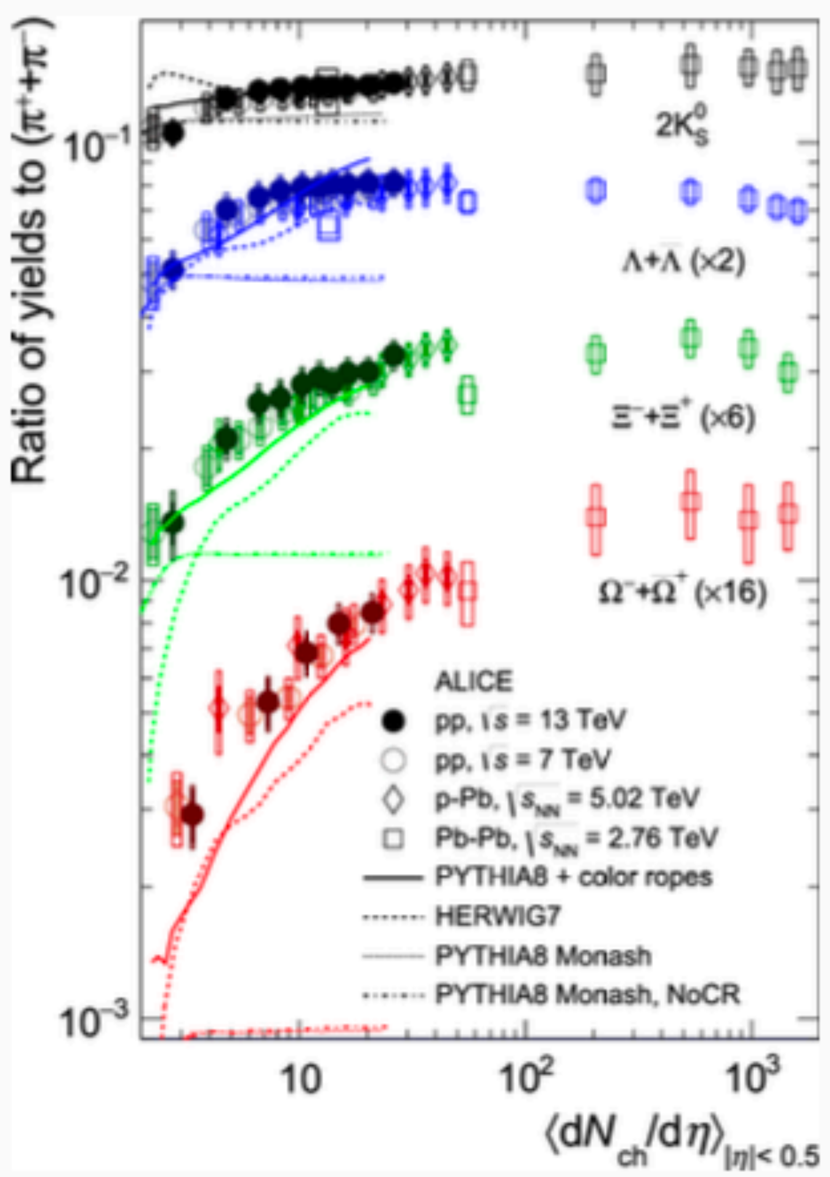
- Is the implementation of core-corona in EPOS a reasonable proxy for thermal hadronization in small systems?
- Is the outcome result a trustworthy representation of how one would expect models to behave?
- Would an observation of the splitting in Λ and Ξ ratios disprove QGP in pp?
- Low multiplicity behavior of EPOS?

Part 3: Charm, color reconnection and the case for pA collisions

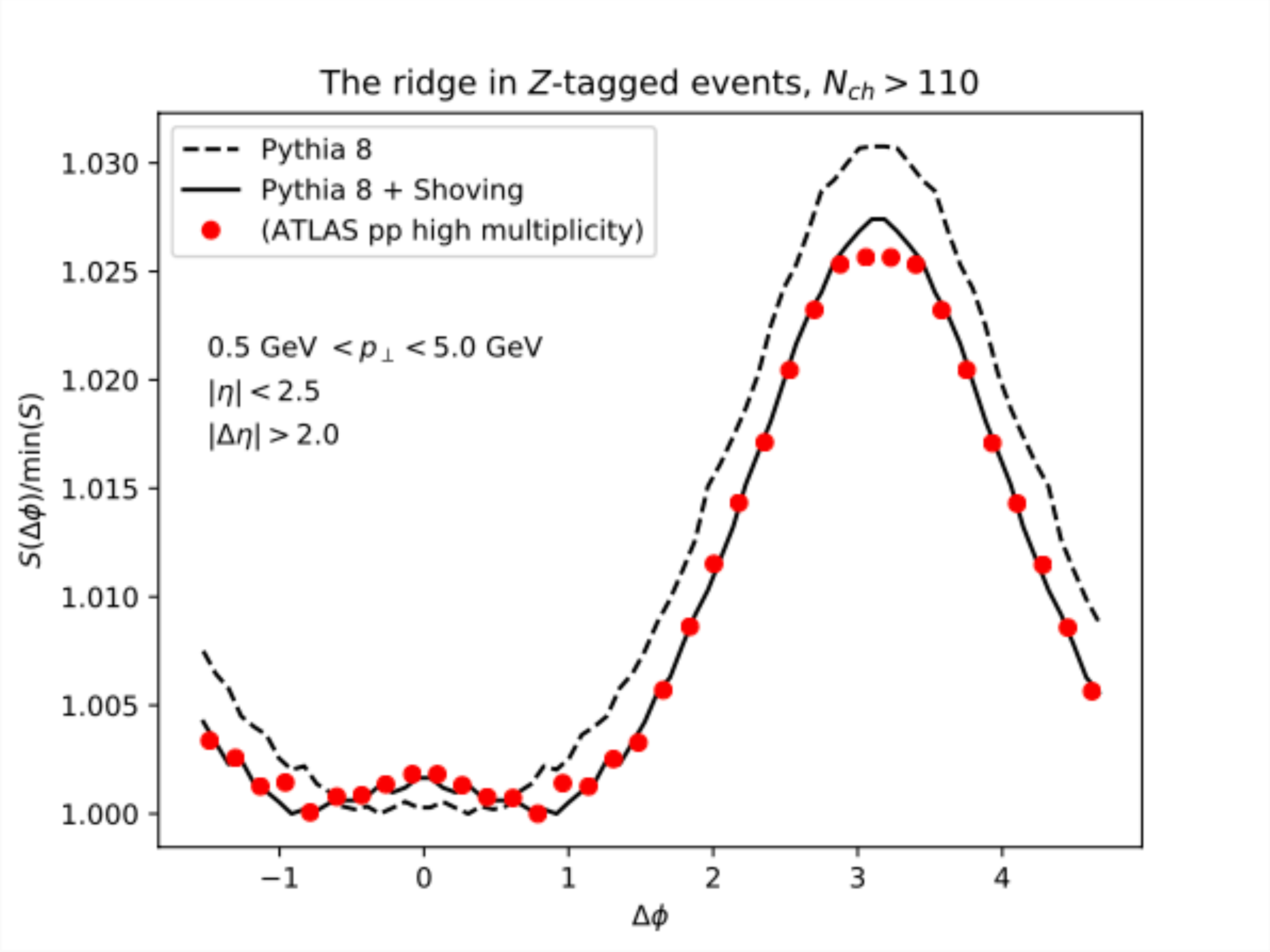
The main “small systems” results

Flow and strangeness

- In our models (interacting strings): string shoving - geometry gives flow, rope hadronization - overlap gives more strangeness.
- Possible hot take: **pp or AA will always be better than pA**

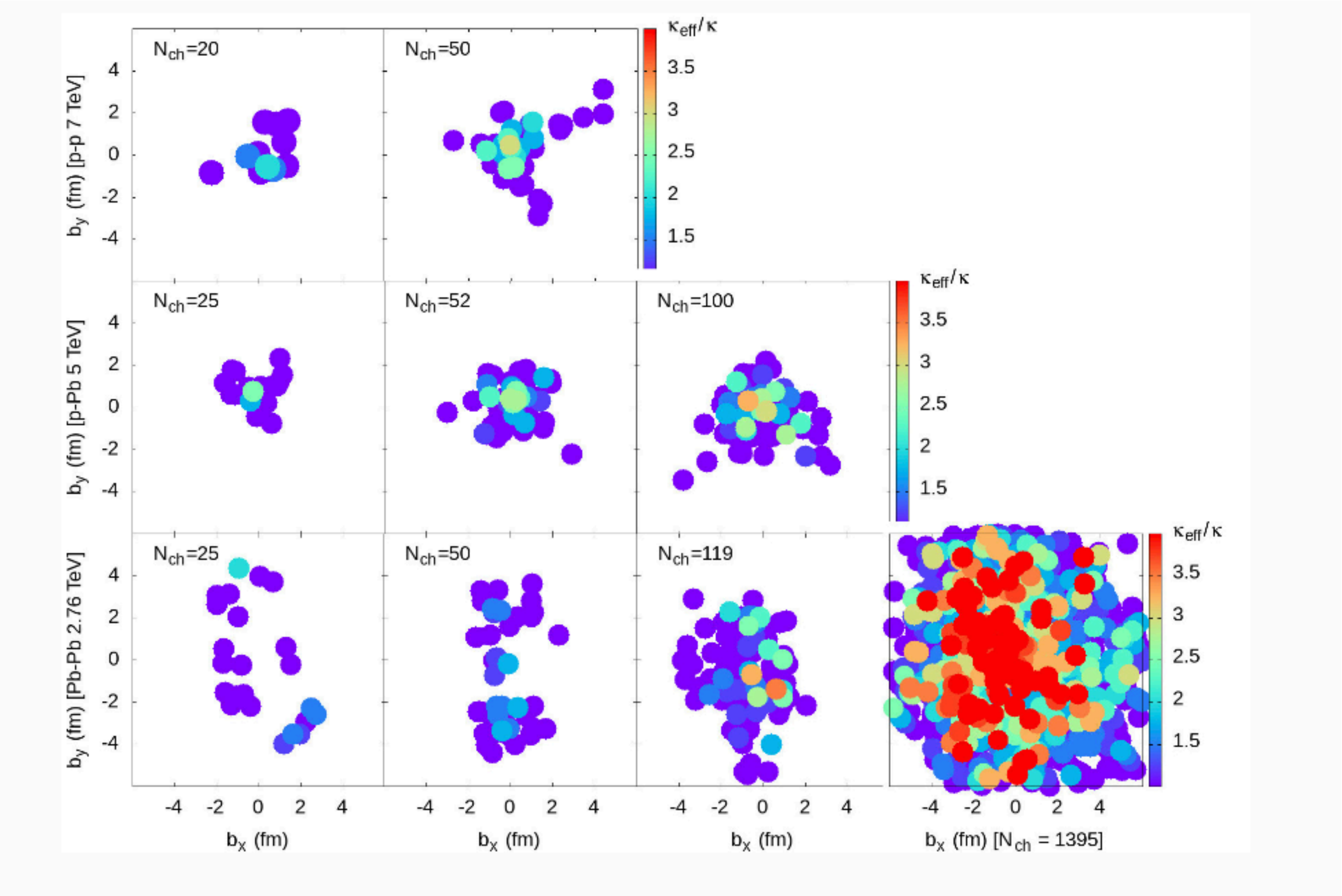


(ALICE (2003.02394))



(ATLAS (1906.08290))

Why? And where would pA shine?



- CR models (vicinity/λ-measure) make pA stand out. You get large transverse size without large energy density!

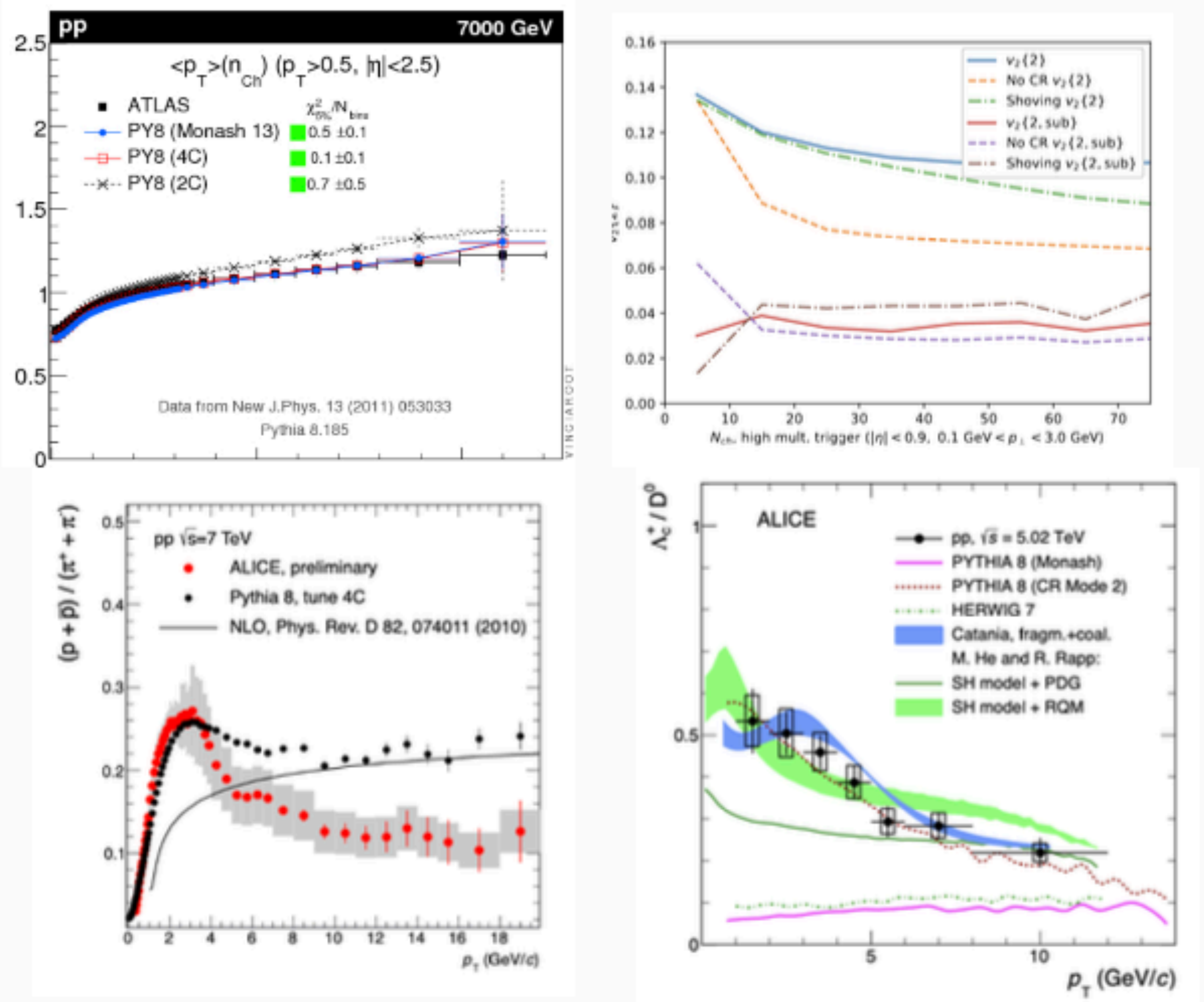
History and LHC surprises

In particular a charming result!

- Reorganize string configuration to correct for $N_c \to \infty$ in parton shower.

- Increasingly important! Charm baryons, essential for strangeness enh., leading contribution to top-mass uncertainty,… (W mass at FCC-ee?)

- **Introduces “collectivity” by definition!**

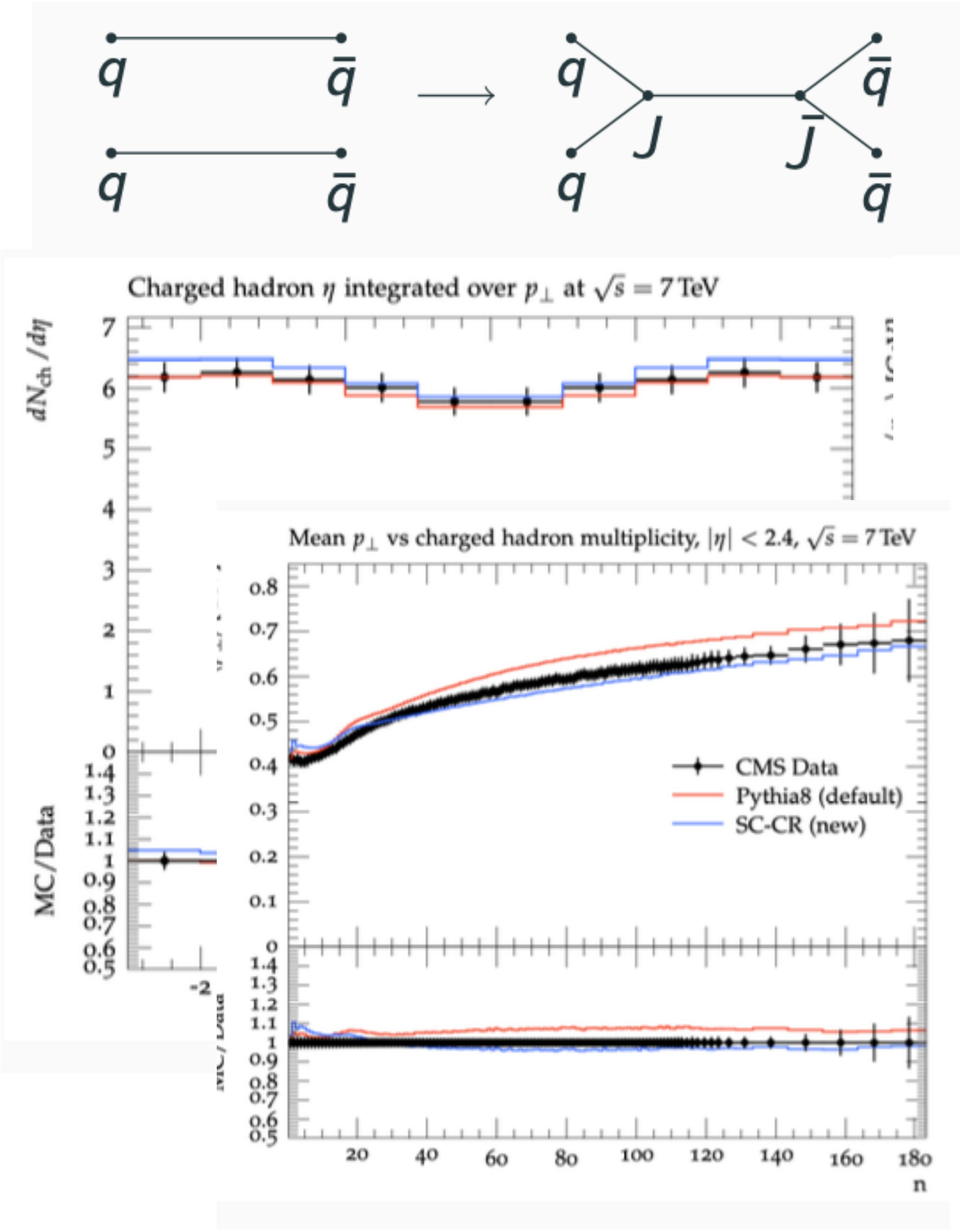


(Figures from: 1303.6326, 1404.5630, 1807.05271, 2011.06078)

CR in heavy ion collisions

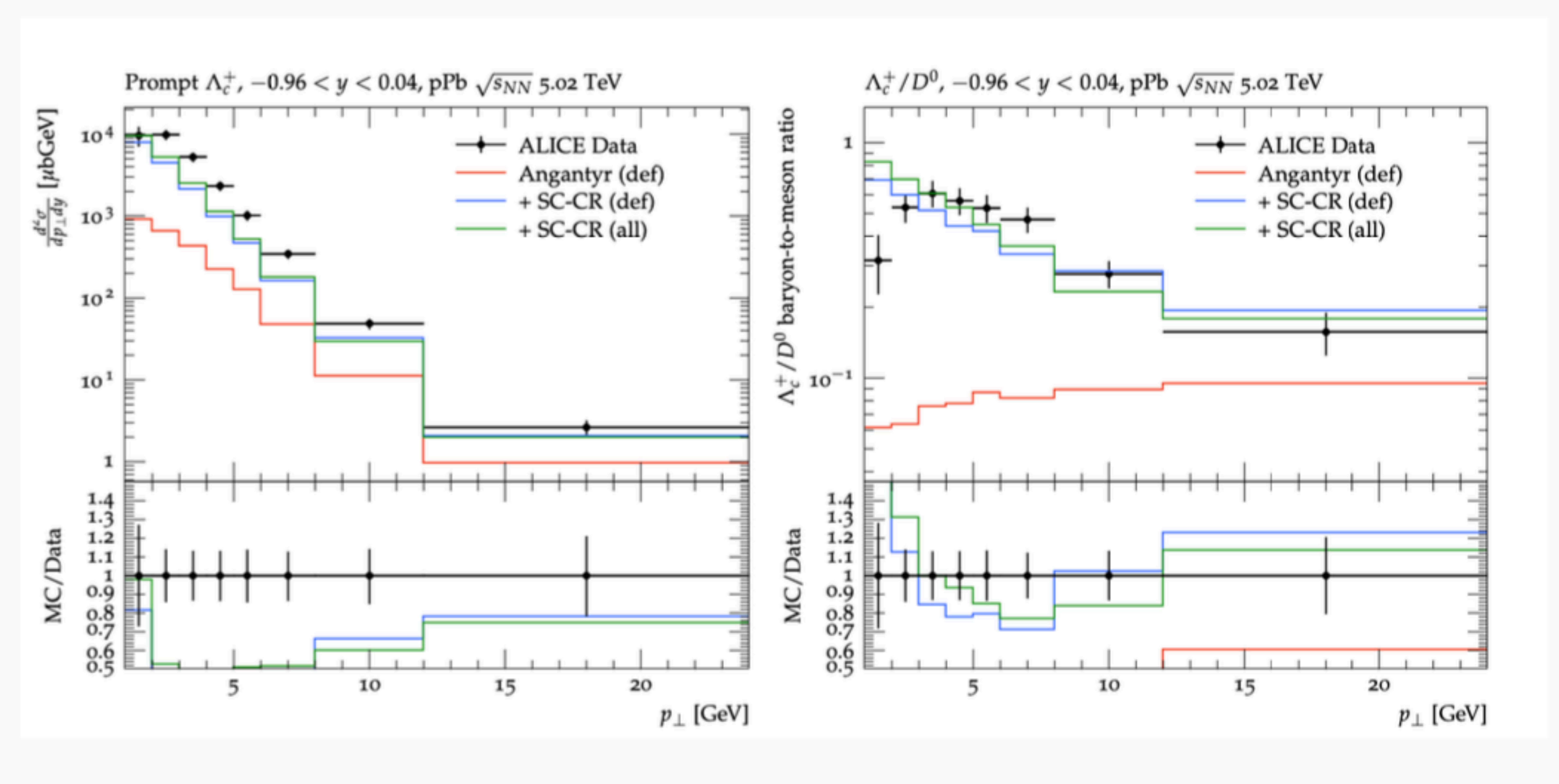
Spatially constrained QCD-CR (2303.11747)

- Starting point: QCD-CR. Disallow reconnections separated in space + retuning. (+ more technical issues)
- All charm produced in hard process + shower.
- Use unique geometric structure of pA.
- Informs particle production mechanisms for **all systems!**



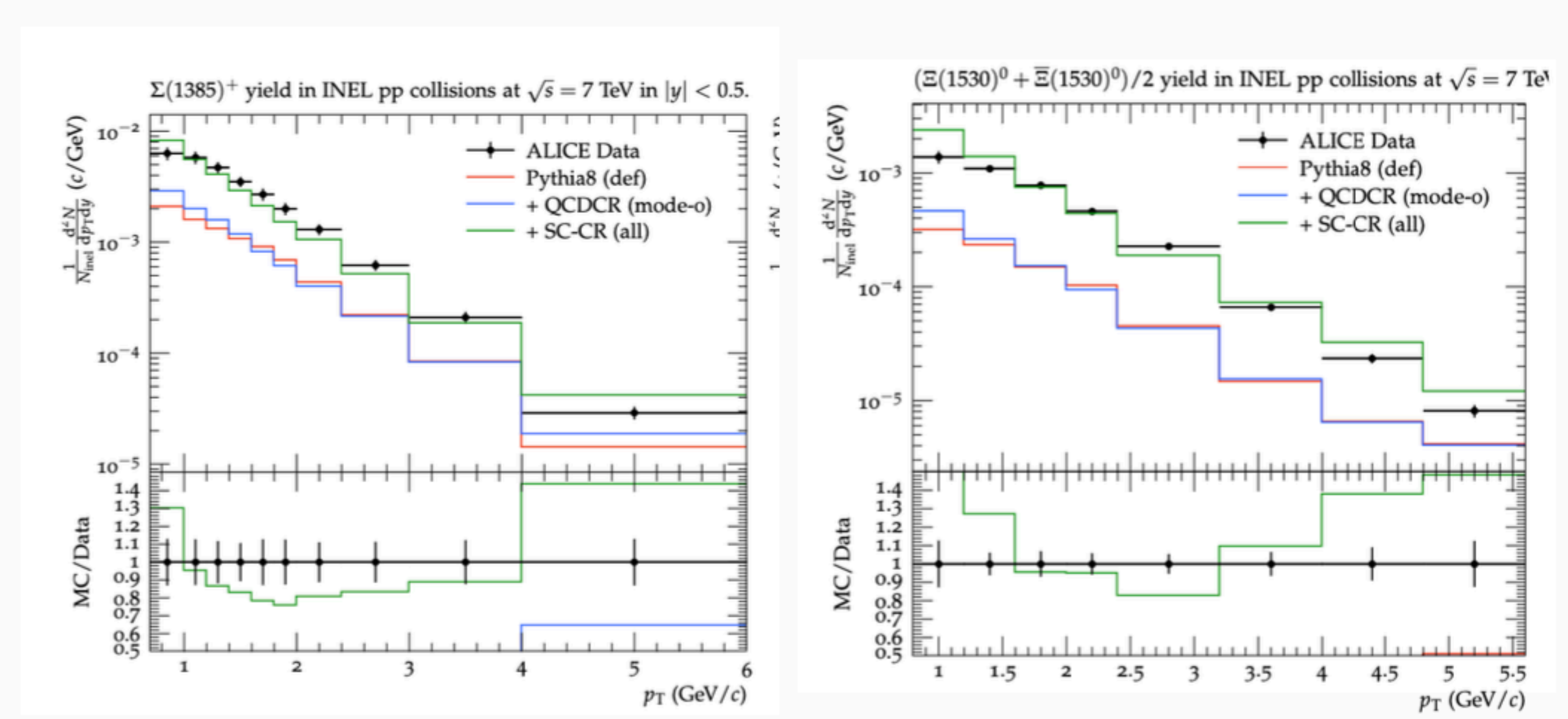
Some results

- First realistic CR in pA does quite well. Increasing strangeness on par with pp.



Some more results

- Revisiting pp with this new recipe. pA physics is now informing pp.



- Insufficient to conclude. But maybe charm is just a repeat of strange?
- Bonus: can one distinguish between CR and recombination? How?