Resonance suppression from color reconnection

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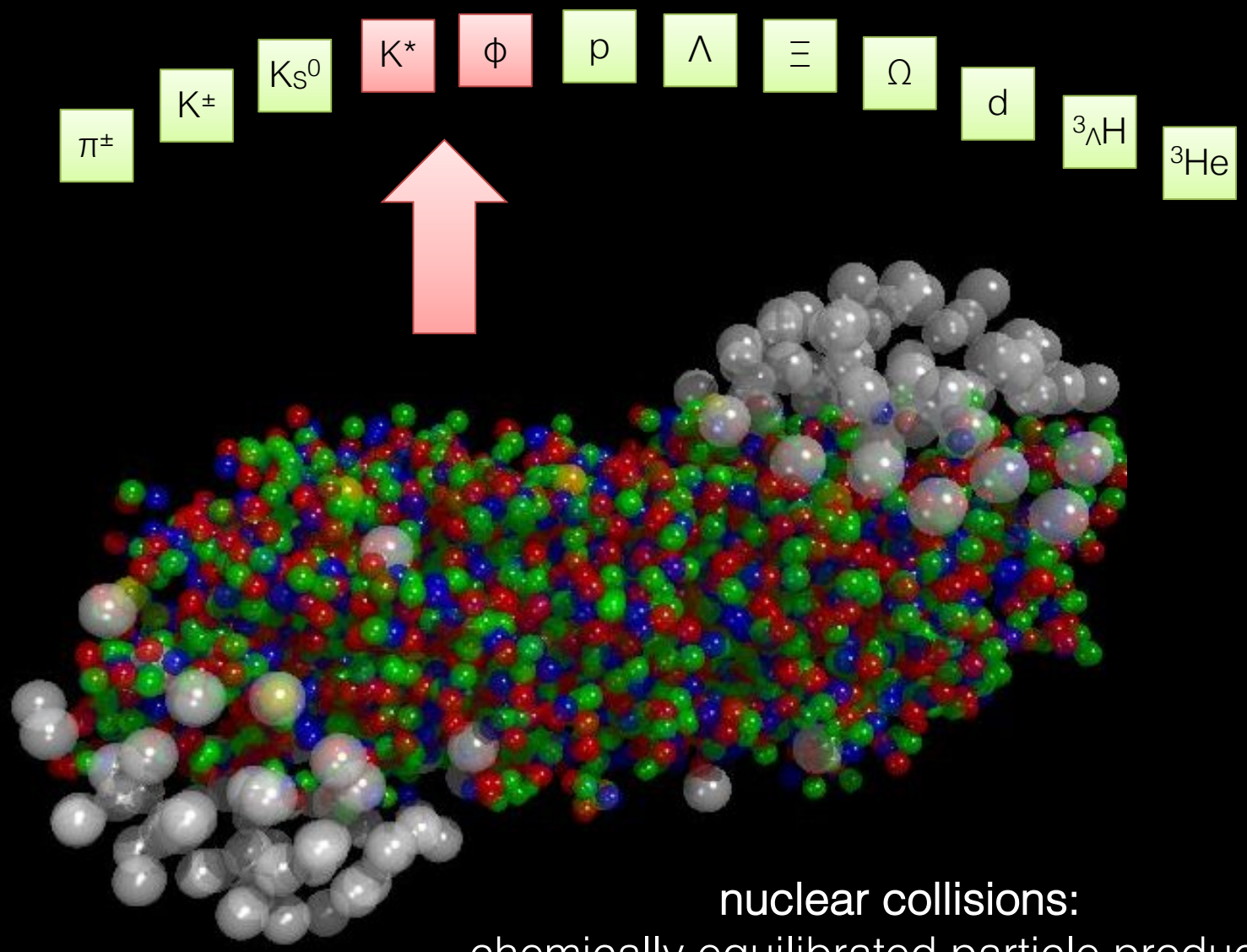
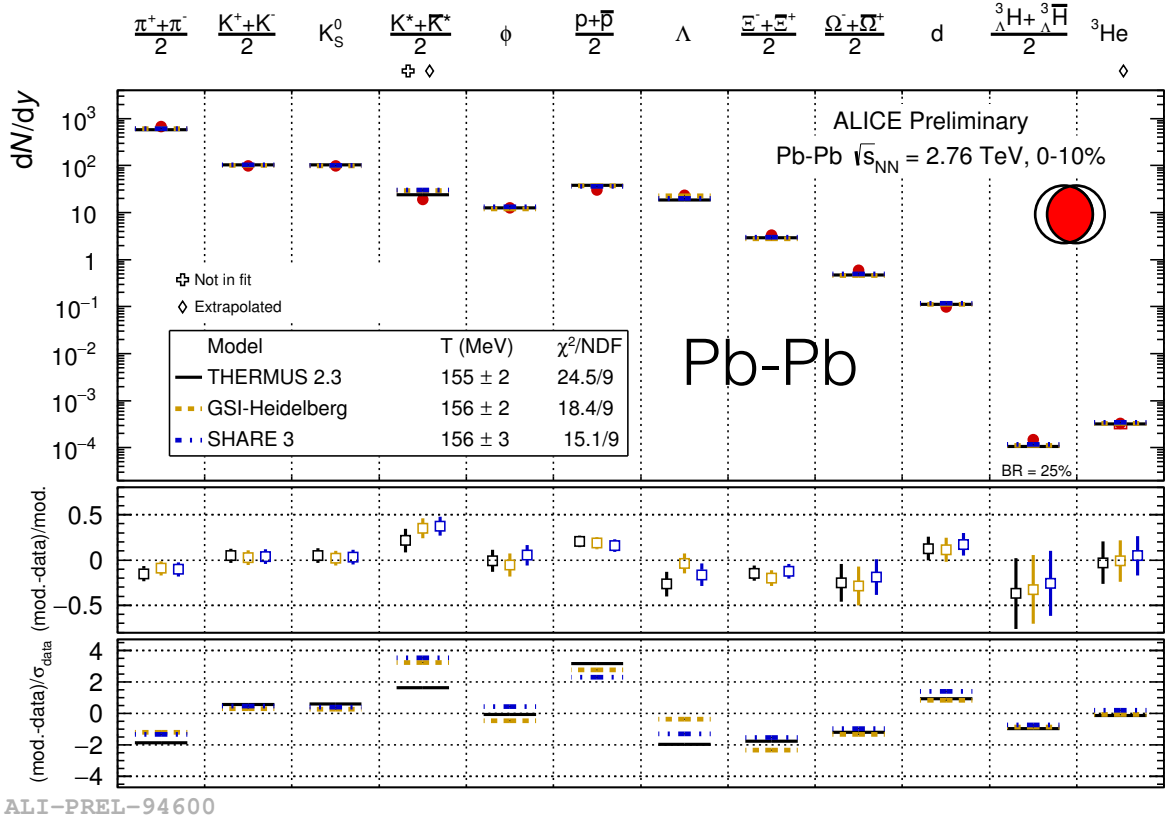
Introduction to resonances: the heavy ion view



nuclear collisions:
chemically equilibrated particle production

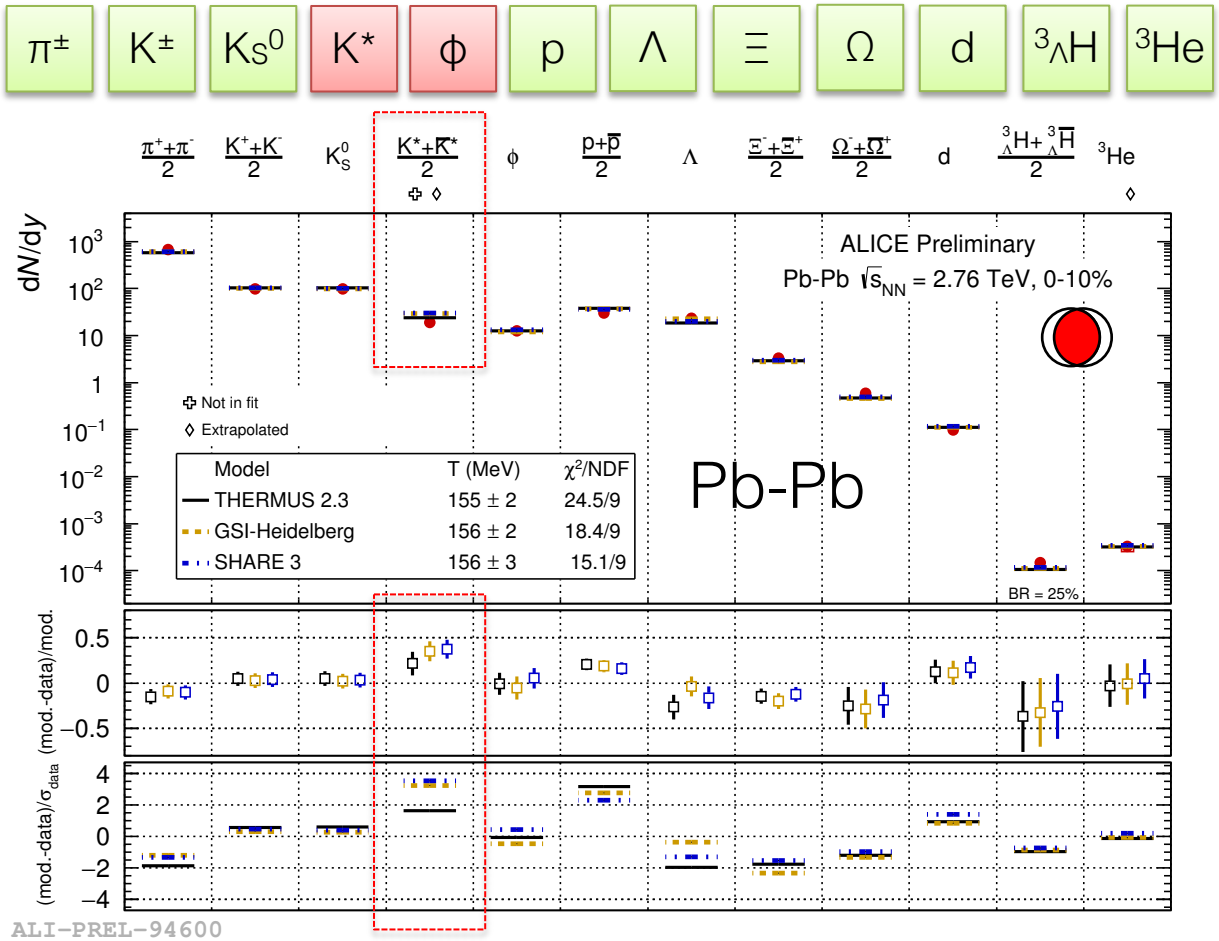
Introduction to resonances: the heavy ion view

$\pi^{\pm}$ | $K^{\pm}$ | K_S^0 | K^* | ϕ | p | Λ | Ξ | Ω | d | $^3_\Lambda H$ | ^3He



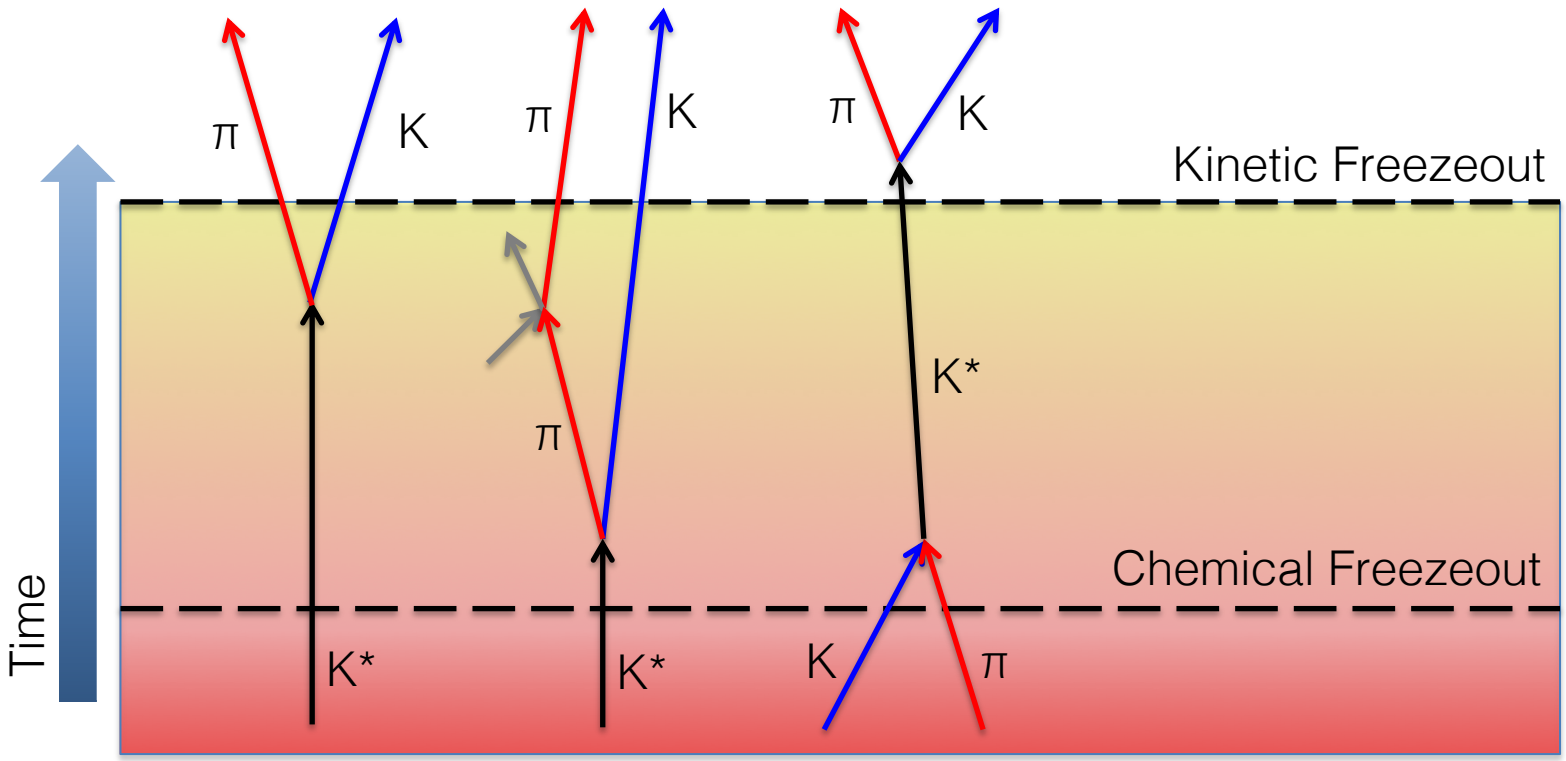
- Description of hadron yields in a thermally equilibrated regime: same conclusions from different implementations, T_{ch} ~156 MeV
- d*N*/d*y* of many species in Pb-Pb well described: χ^2/ndf ~2

Introduction to resonances: the heavy ion view



- However, the description is not good for the K*
- Extra component after hadronization: final state effect?

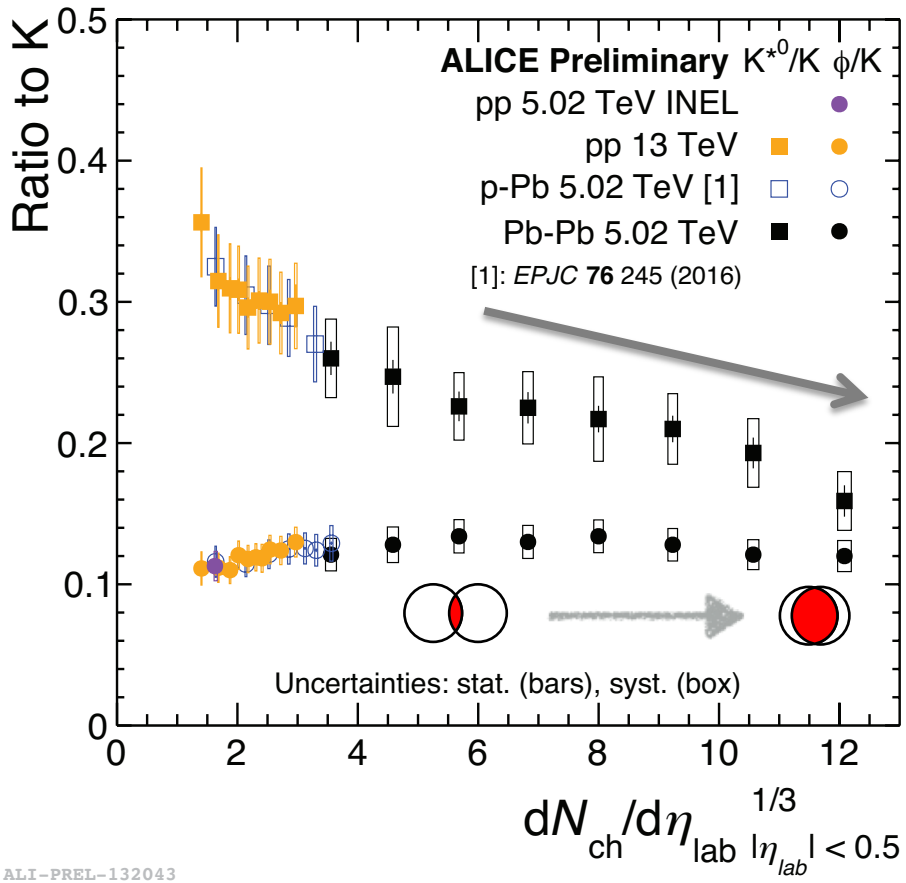
Resonances, Rescattering and Regeneration



- Consider the short-lived K* resonance (~4 fm/*c*)
  - Usual scenario: decay in the hadronic phase
  - Daughters may re-scatter and yield may not be visible
  - Regeneration (pseudo-elastic scattering) may recover part of the yield

Resonances: probe (the duration of) the hadronic stage

K* and ϕ production rates in Pb-Pb vs pp, p-Pb



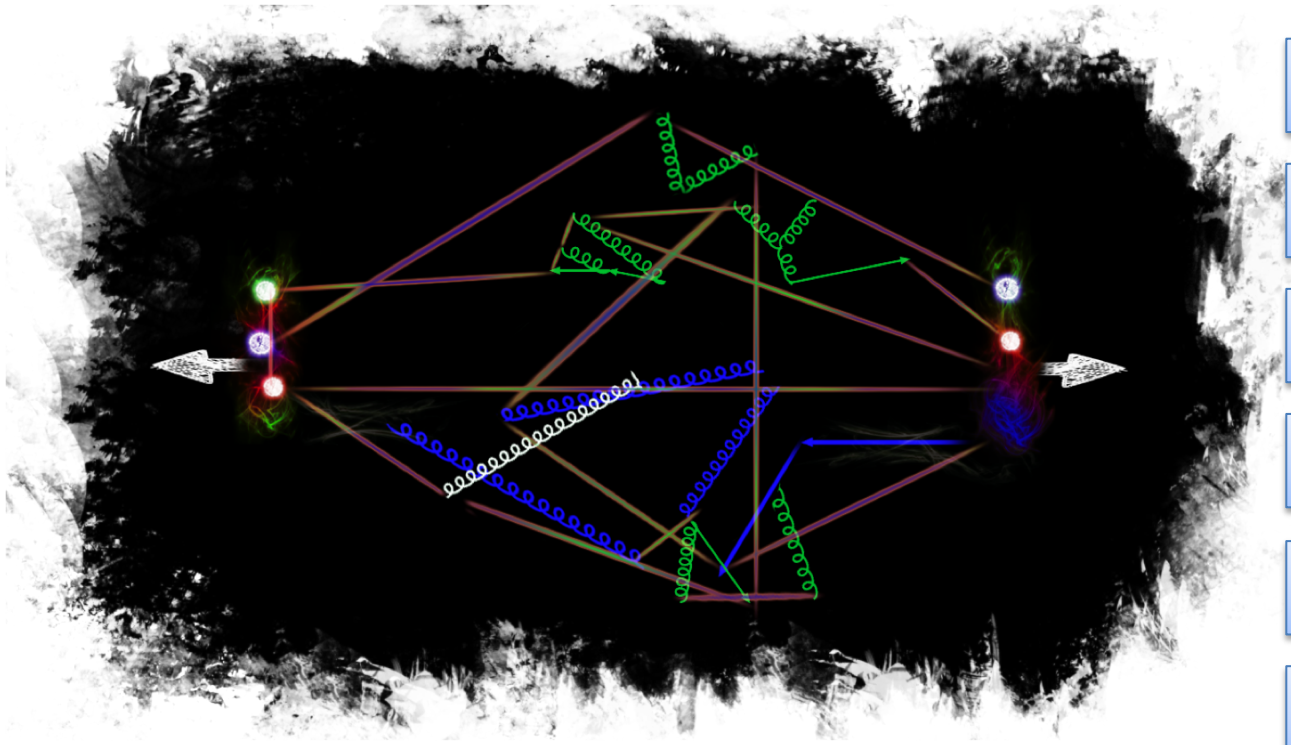
- Clear suppression observed in K*/K⁻ when going from pp to central Pb-Pb collisions: present vs multiplicity for all systems!
- Could there still be rescattering even in pp and p-Pb collisions?
  - UrQMD says no: system too small, would be negligible!

- Can we look at alternative mechanisms for this K* yield reduction?

Simulating pp: The PYTHIA event generator

- Monte Carlo event generator developed originally by the Lund group;
- Generates events based on
  - scattering amplitude from pQCD
  - additional empirical corrections
- Simulates the entire event, including hadronization, allowing for any experimental observable to be predicted
- Multi-purpose (e^+e^-, pp and more)

A proton-proton collision for PYTHIA

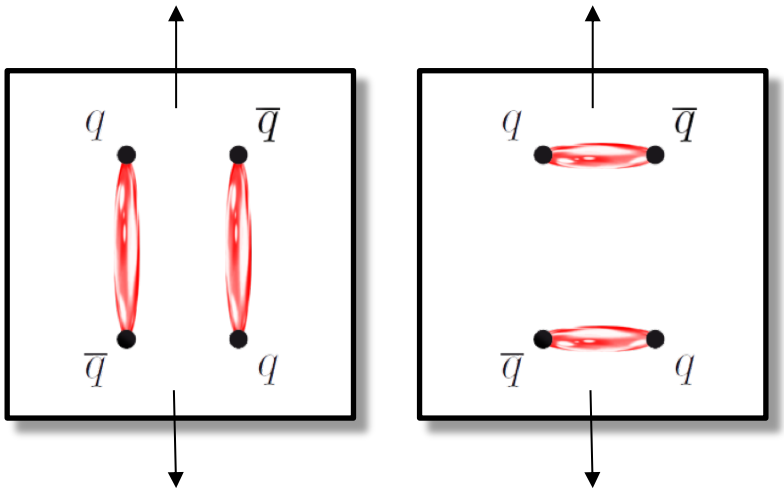


- Parton momenta: p.d.f.
- Multiple interactions (MPI)
- Initial state radiation (ISR)
- Final state radiation (FSR)
- Color (re)connection (CR)
- Hadronization, decays

Final Partons of the Event connected via **color confinement** strings and **hadrons are created + decayed**

Multiple string hadronization: non-trivial, many approaches

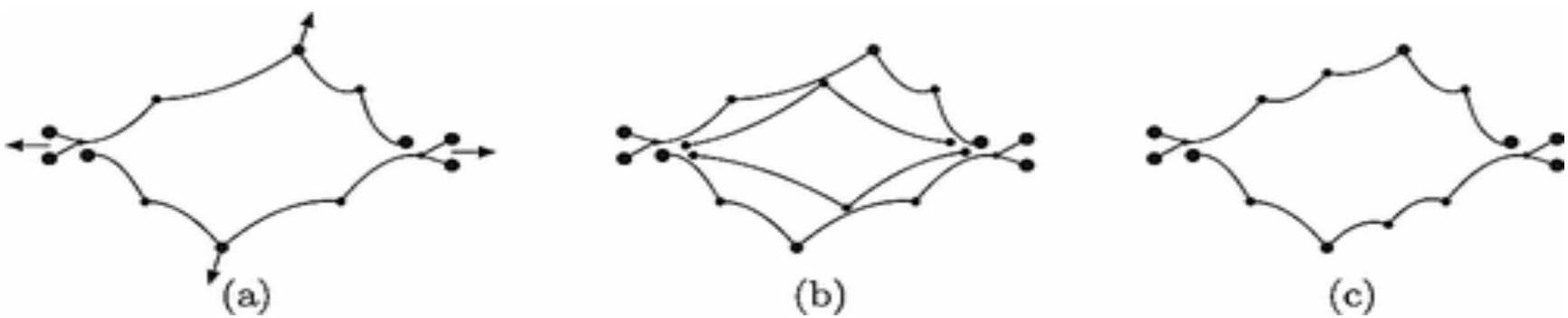
Multiple string hadronization: the problem



- In PYTHIA: fragmentation via 'string' breaking: flux tubes of interacting gluons of approximately constant energy density
- If **MPIs** available: which string arrangement should be used?

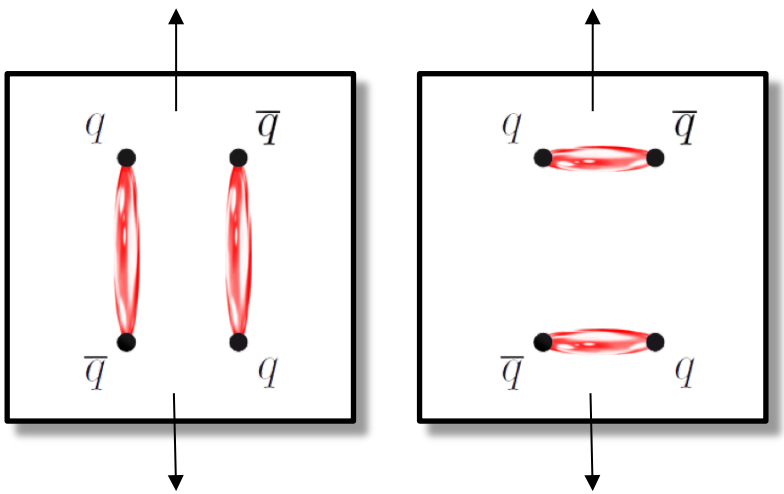
G. Gustafson, Acta Phys. Polon. **B40**, 1981 (2009)

"**MPI-based**" CR scheme



First Interaction | Second Interaction | Color reconnection

Multiple string hadronization: the problem



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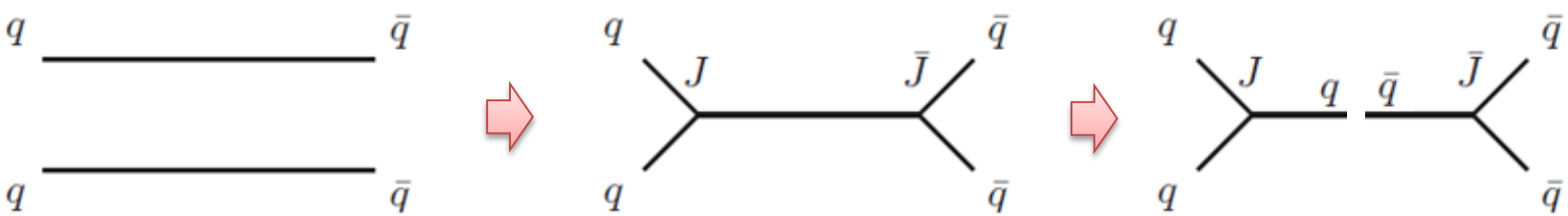
"More QCD-based" CR scheme

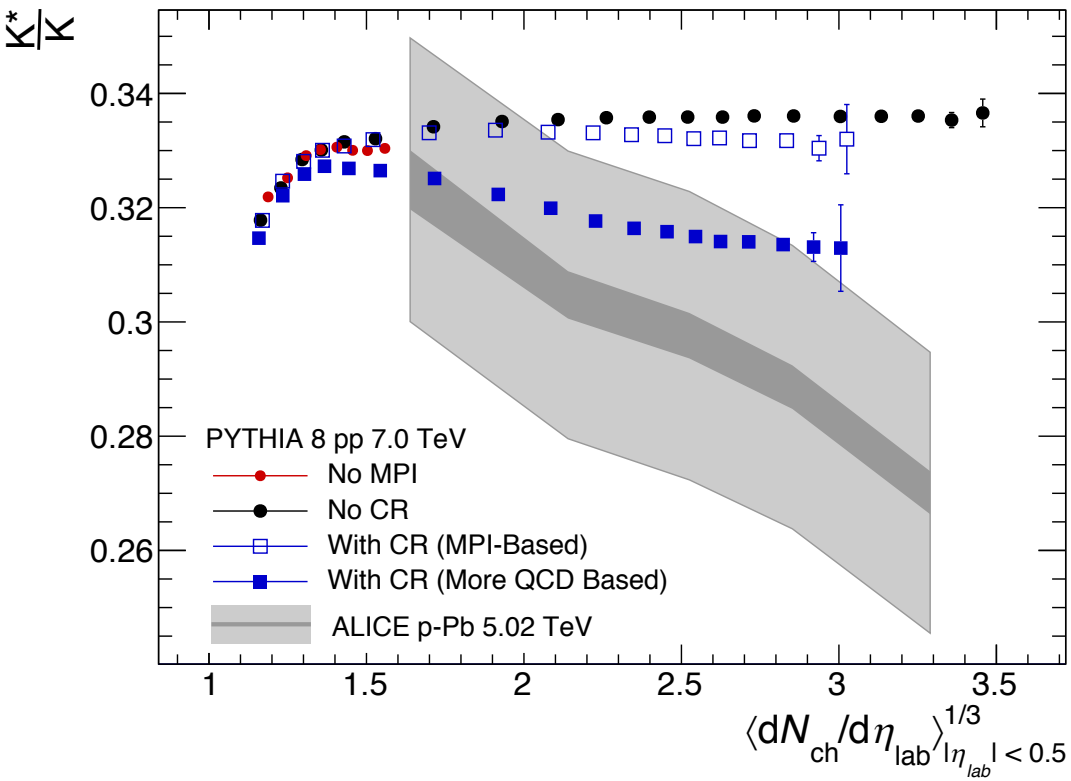


Are there other ways to connect? → Yes! Introducing 'junctions'

…originally introduced to improve the description of baryon production

The K*/K ratio in PYTHIA

p-Pb: Eur. Phys. J. C (2016) 76:245

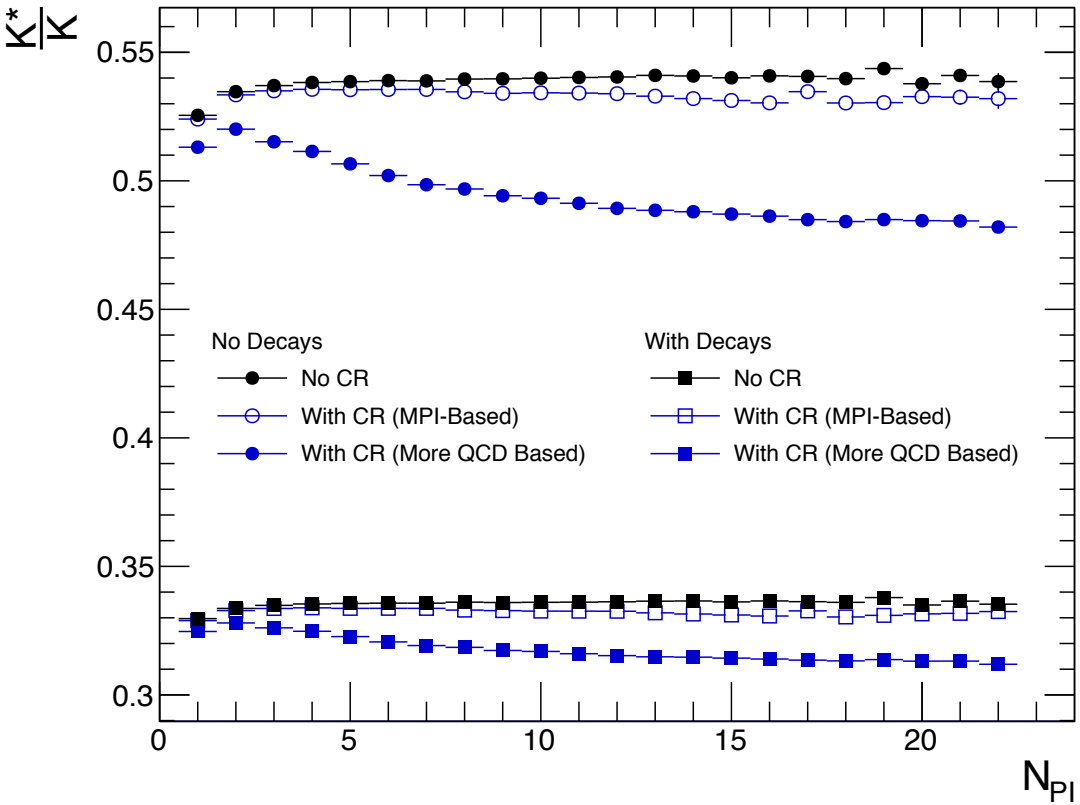


- Single parton interaction: baseline K*/K ~0.33
- Multiple interactions: higher N_{ch}, K*/K at baseline value
- MPI-based CR: no significant change
- More-QCD based CR: signs of suppression?
- Effect within uncertainties of p-Pb (borderline)?

→ What is the origin of this suppression?...

…could this be due to particle decays?

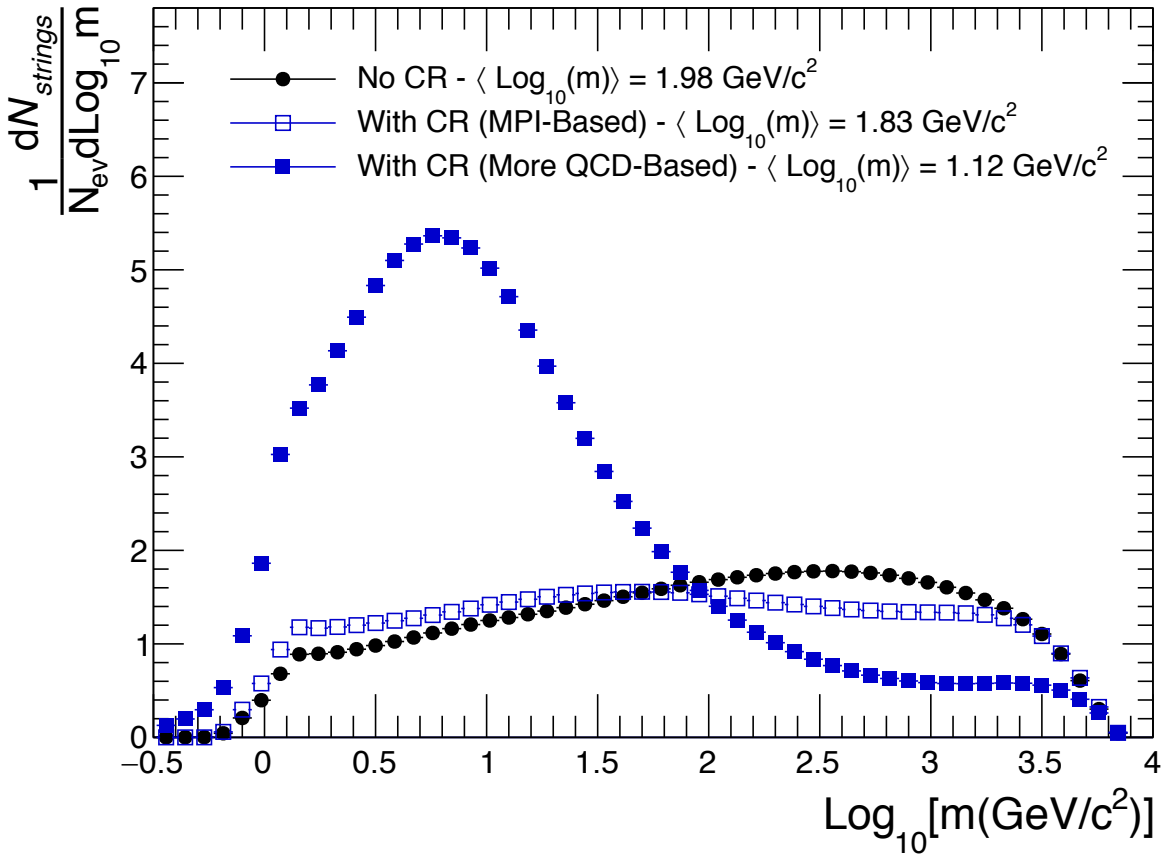
The K*/K ratio and the role of decays



- If all particles are allowed to decay, resonances will feed into the K (but not the K*)
- Tested by looking at the K*/K directly after hadronization (all decays disabled)
- Suppression still there!

Let's study the strings that produced these mesons…

String mass distribution



- For strings: length ∝ energy
- CR produces shorter strings, especially in the More QCD-based scheme
- How does this depend on number of parton-parton interactions?

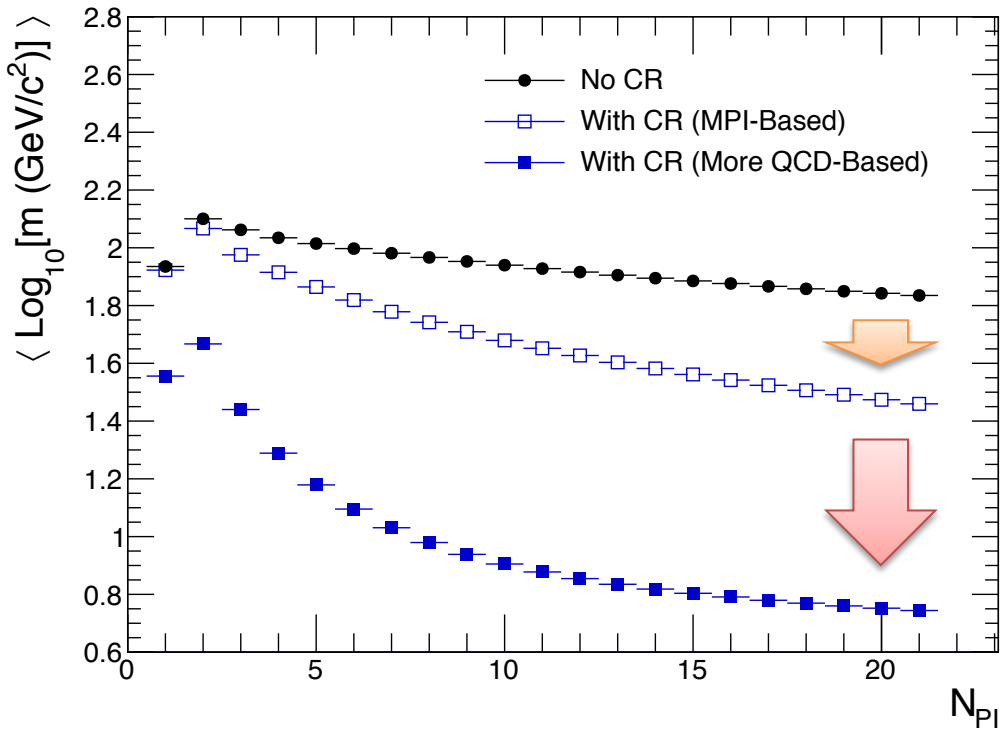
String mass distribution

- String lengths:

  No CR > MPI-based

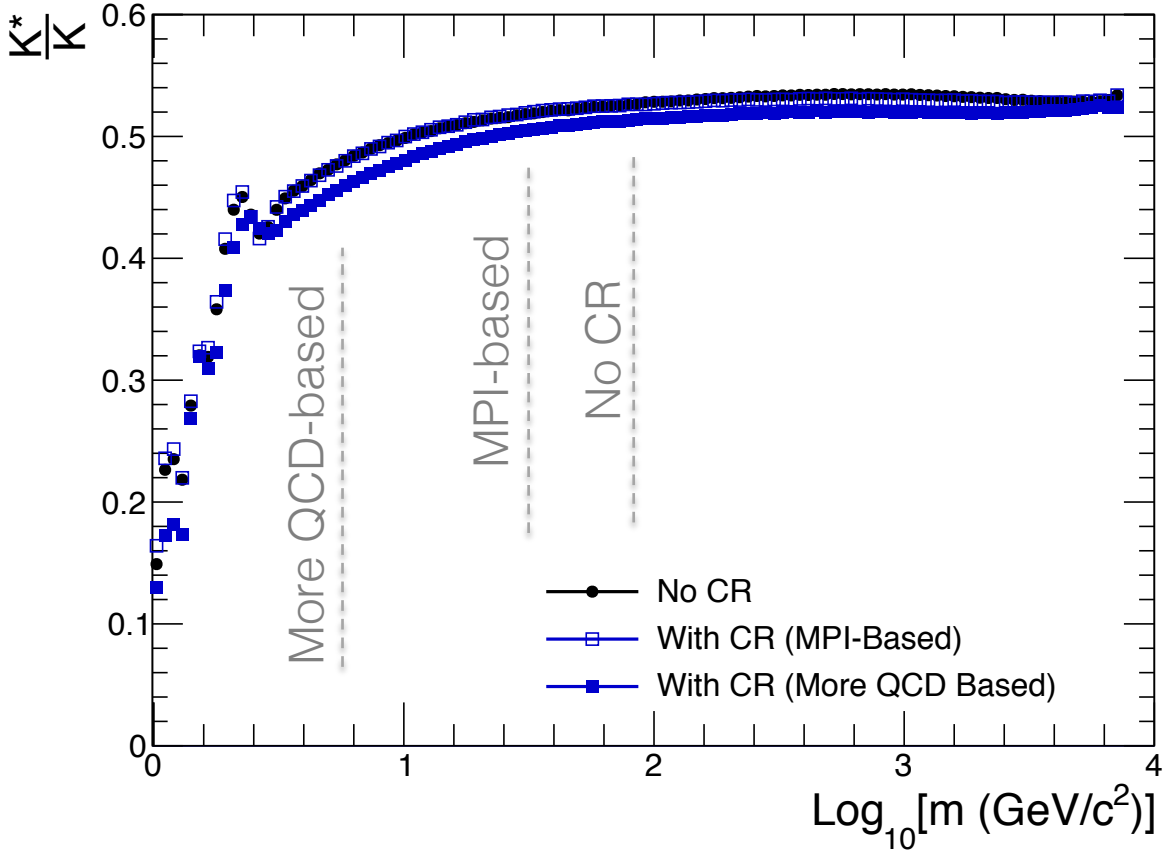
  MPI-based > More QCD-based

- Effect is most important for high N_{PI} -> high multiplicity!



→ What about K*/K for a given string mass?

The K*/K vs string mass



- Vertical lines: averages for each CR scheme at N_{PI} = 20
- Suppression from lower average string mass
- Similar behaviour for ρ_0/π and η'/π as well

Conclusions

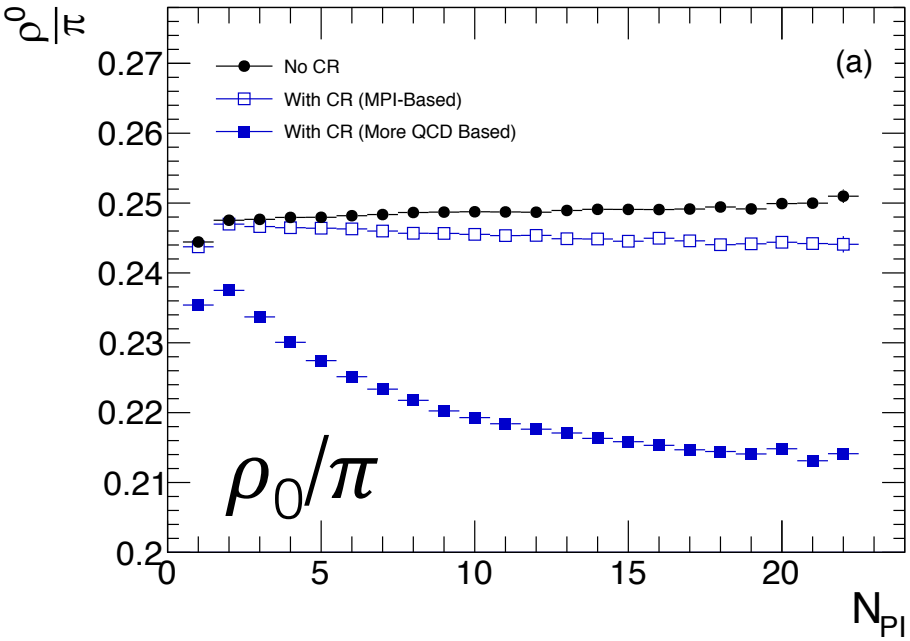
- Traditional heavy ion picture:
  - Short-lived resonances suppressed because of rescattering
- From pp pQCD-inspired models:
  - They may also be suppressed in high-density hadronization because of shorter strings
  - This conclusion was drawn in a specific CR scheme but the mechanism is general.

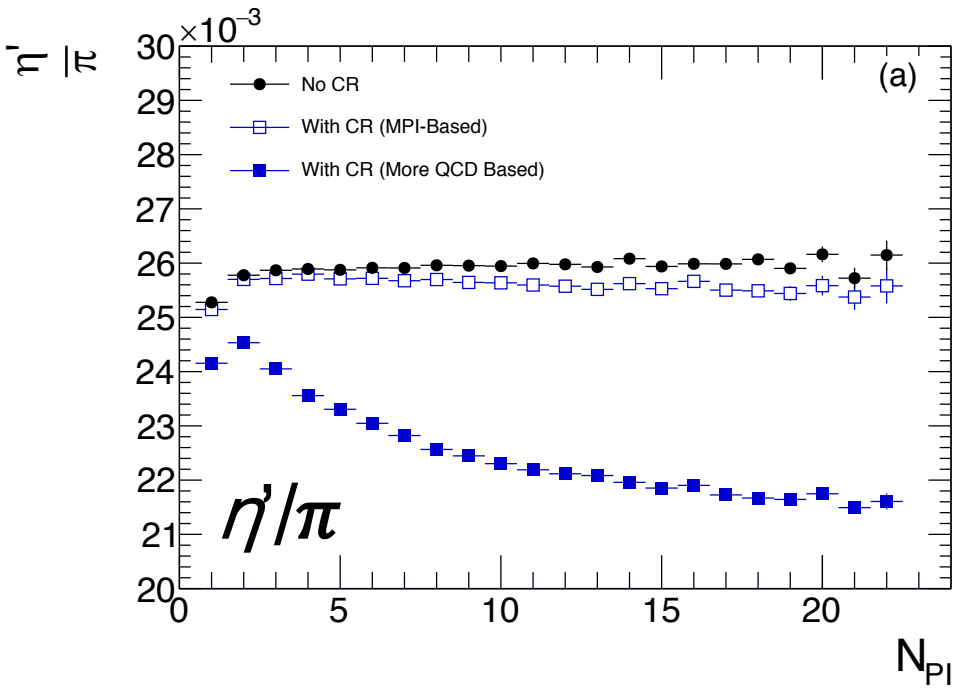
- ❑ Could we use resonance suppression to tune CR? How much suppression could CR account for?
- ❑ What about baryonic resonances? Description harder in pQCD-inspired models, more parameter-dependent: more study needed
- ❑ How to distinguish experimentally? Is hadron mass or lifetime the driving factor in suppression measurements?

Thank you!

Backup

Other resonances: the ρ_0/π and η'/π

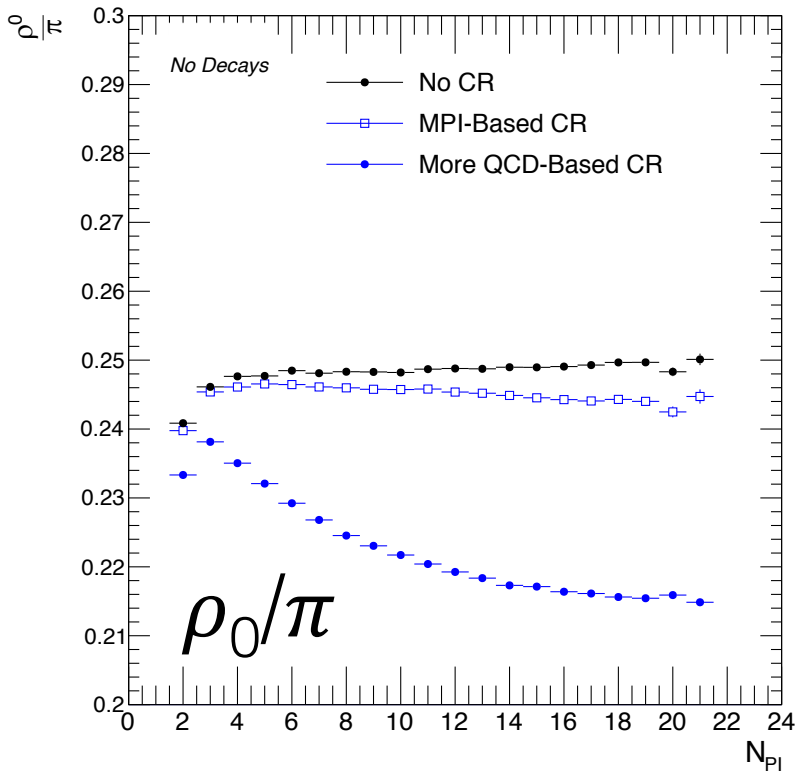


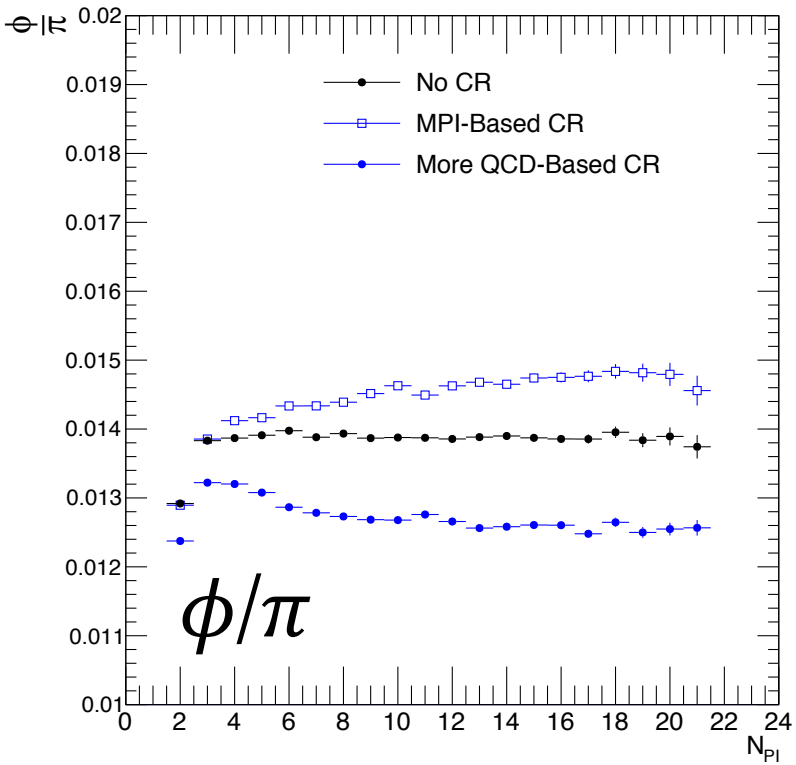


- ρ_0/π: also affected by rescattering in classical picture
  → Smaller strings also reduce this ratio!

→ η'/π: interesting, η' is spin zero
  → Spin has nothing to do with this suppression

Other resonances: the ρ_0/π and ϕ/π

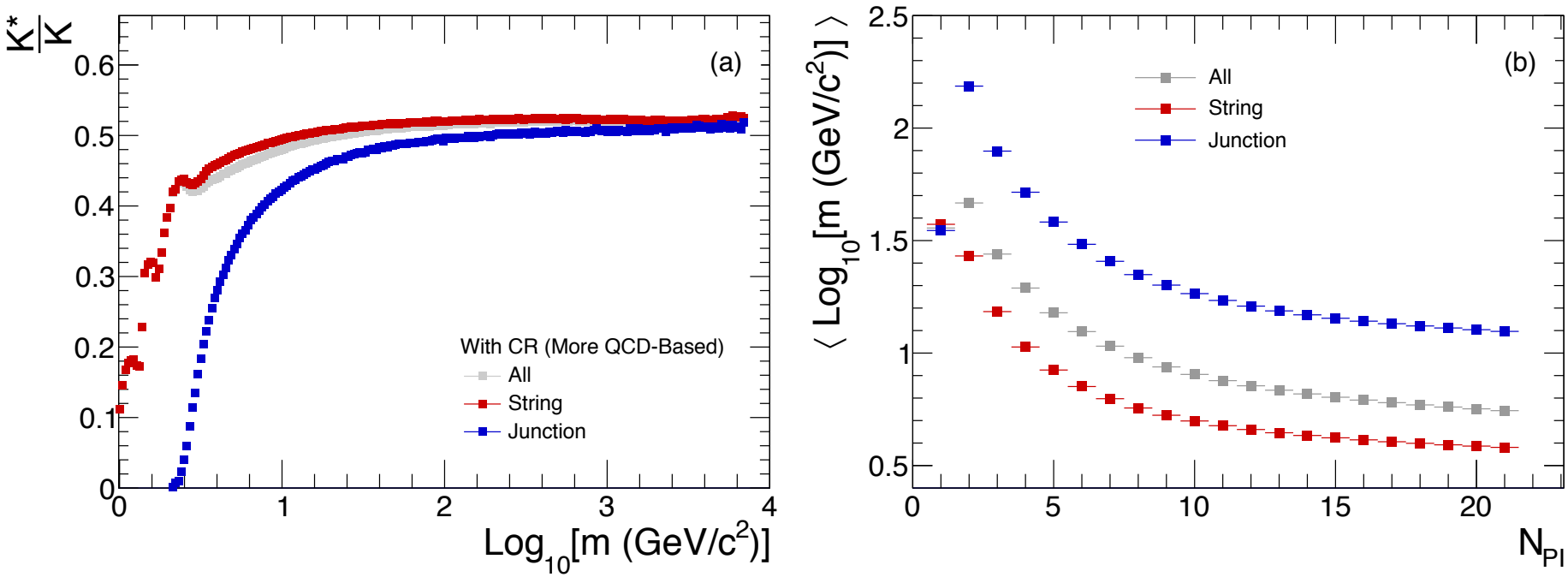




- ρ_0/π: also affected by rescattering in classical picture
  → Smaller strings also reduce this ratio!
- ϕ/π: no suppression in classical picture but beware different quark content, more investigation required

The K*/K for $q\bar{q}$ strings and junctions

In the More QCD-based scheme



- General reduction of average mass for both cases
- At lower masses, junctions prefer forming baryons, leading to lower K*/K ratios
- But: qq strings still responsible for majority of K, K* production -> majority of suppression

K*/K and the lifetime of the hadronic phase

- Model of Torrieri, Rafelski et al predicts particle ratios as a function of chemical freeze-out temperature and lifetime of hadronic phase
- Model predictions:

Torrieri/Rafelski
no re-scattering
T_{ch} = 156 MeV

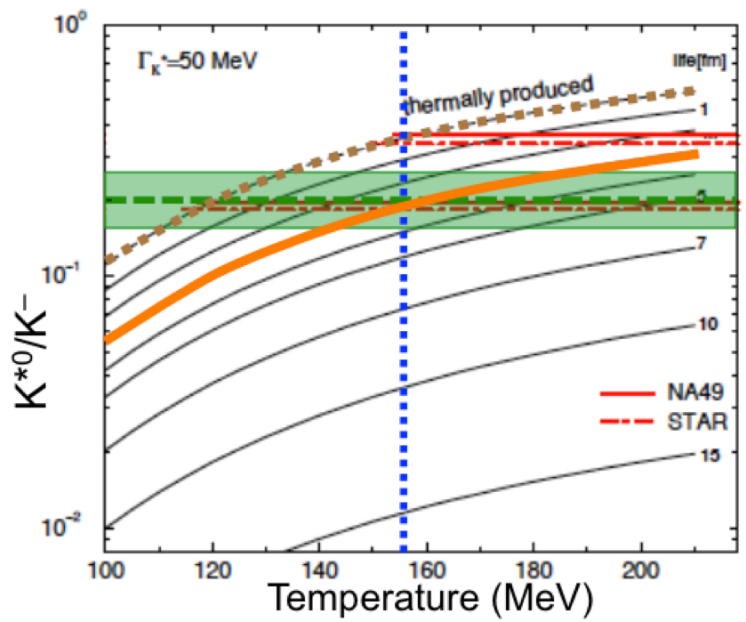
→ Prediction:
K^{*0}/K^0 = 0.35

Torrieri/Rafelski
no re-scattering
measured K^{*0}/K^0

→ Prediction:
T_{ch} = 120 MeV

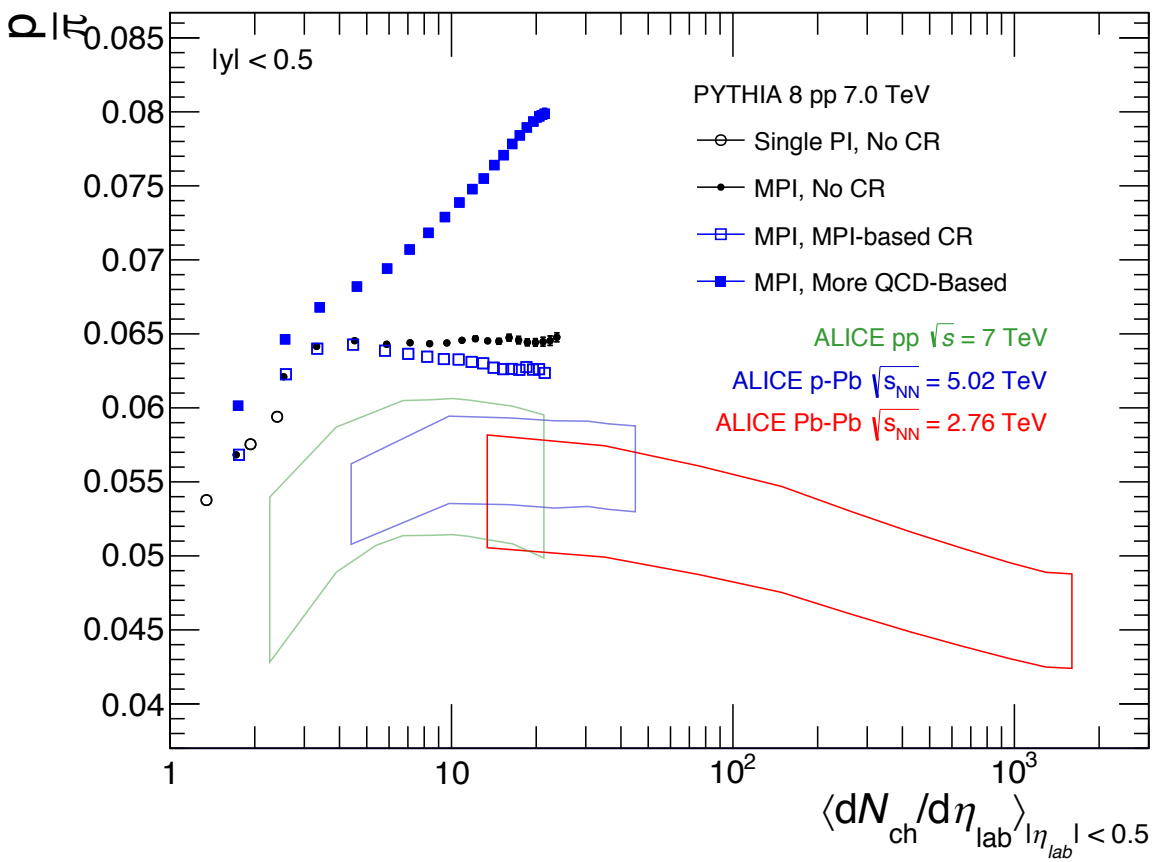
Torrieri/Rafelski
measured K^{*0}/K^0
T_{ch} = 156 MeV

→ Prediction:
Lifetime ≥ 2 fm/*c*



*References:
G. Torrieri and J. Rafelski, *J. Phys. G* **28**, 1911 (2002)
J. Rafelski *et al.*, *Phys. Rev. C* **64**, 054907 (2001)
J. Rafelski *et al.*, *Phys. Rev. C* **65**, 069902(E) (2002)
C. Markert *et al.*, arXiv:hep-ph/0206260v2 (2002)

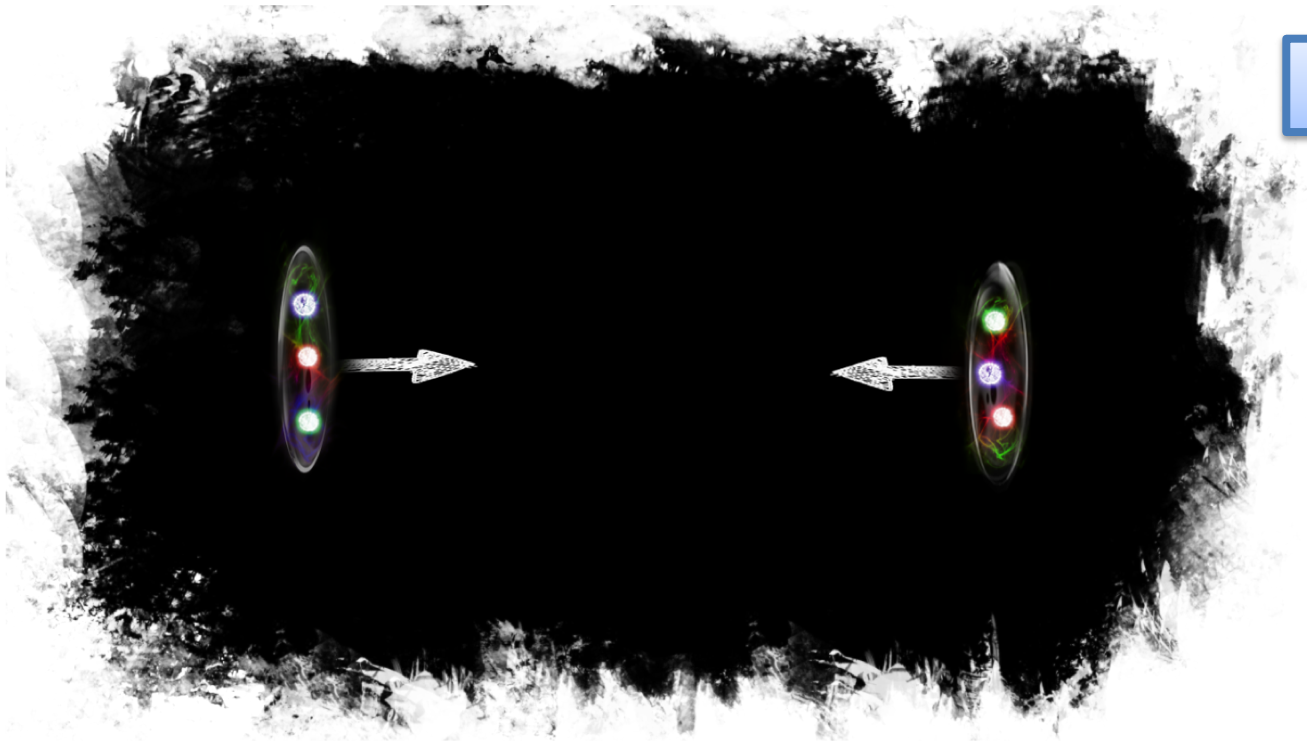
Baryon production: p/π



- Single parton interaction: baseline p/π ~0.06
- Multiple interactions: higher N_{ch}, no significant change in ratio
- More QCD-based: p/π increases, contrary to data

pp: Nature Physics 13, 535–539 (2017)
p-Pb: Phys. Lett. B 728 (2014) 25-38
Pb-Pb: Phys. Rev. C 88, 044910 (2013)

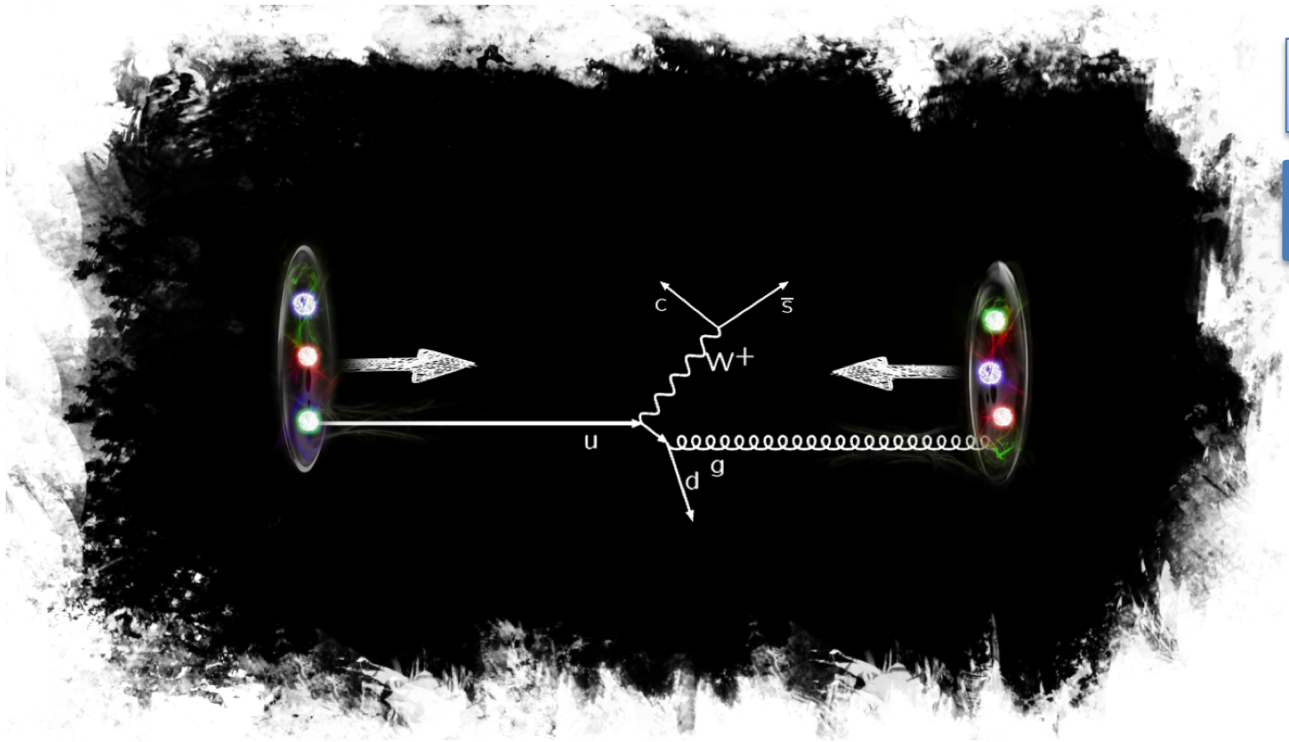
A proton-proton collision for PYTHIA



Parton momenta: p.d.f.

Select interacting **parton momenta** from p.d.f

A proton-proton collision for PYTHIA



Parton momenta: p.d.f.

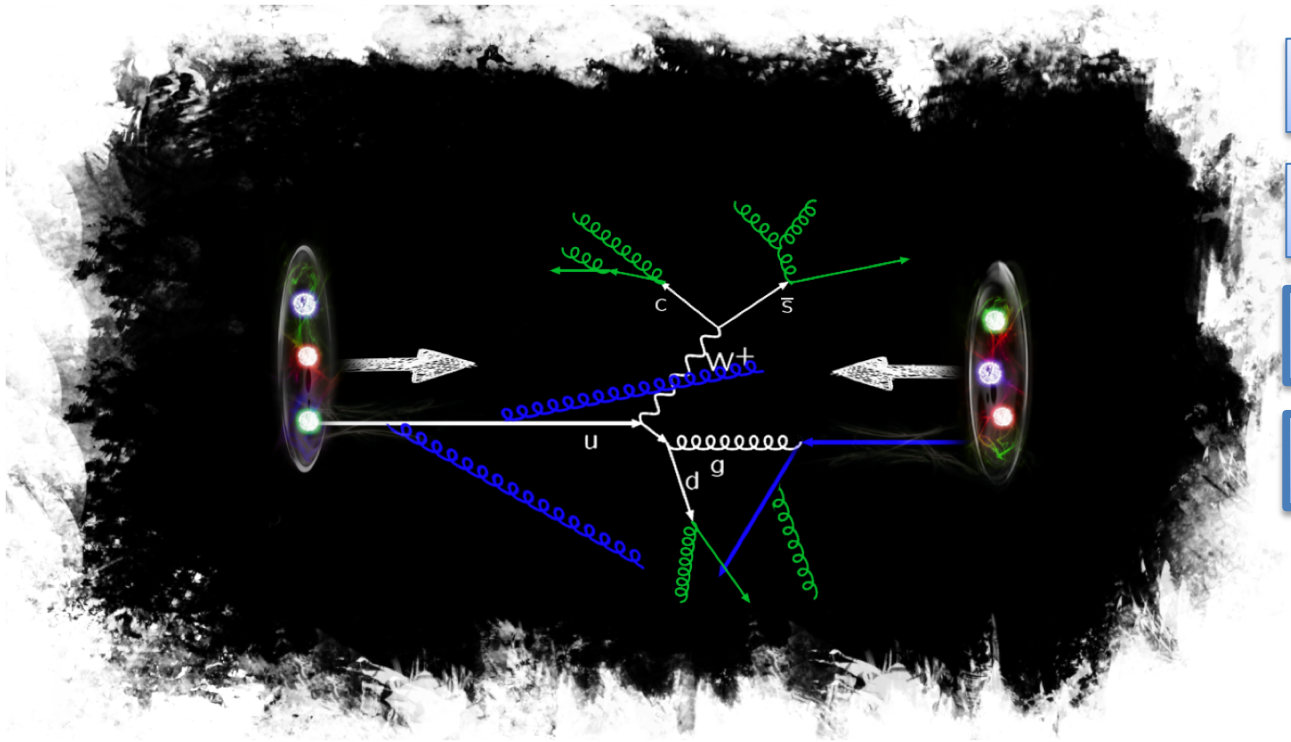
Hard Parton interaction

Single **Hard Parton** Interaction

+ Resonance **Decays**

(**N.B.**: 'resonance' in this context:
"all particles with mass above the b quark system")

A proton-proton collision for PYTHIA



Parton momenta: p.d.f.

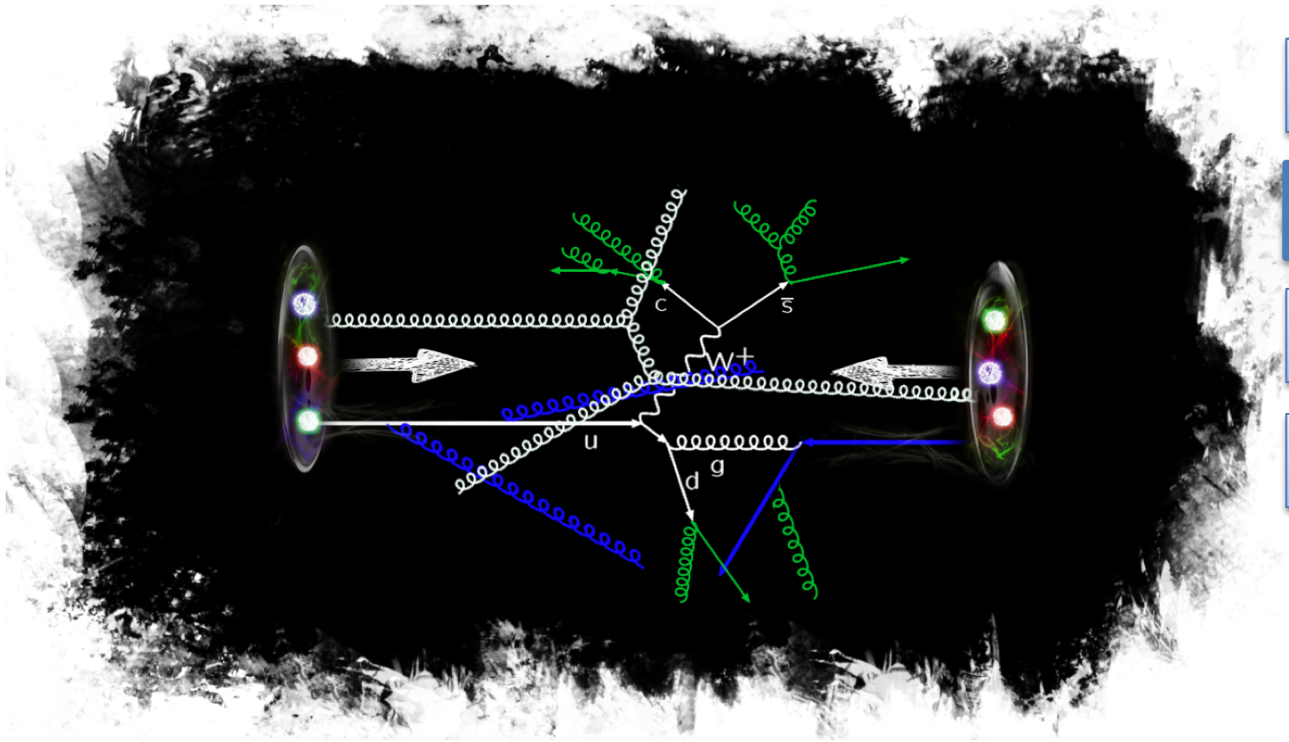
Hard Parton interaction

Initial state radiation (ISR)

Final state radiation (FSR)

Initial and Final State Radiation

A proton-proton collision for PYTHIA



Parton momenta: p.d.f.

Multiple interactions (MPI)

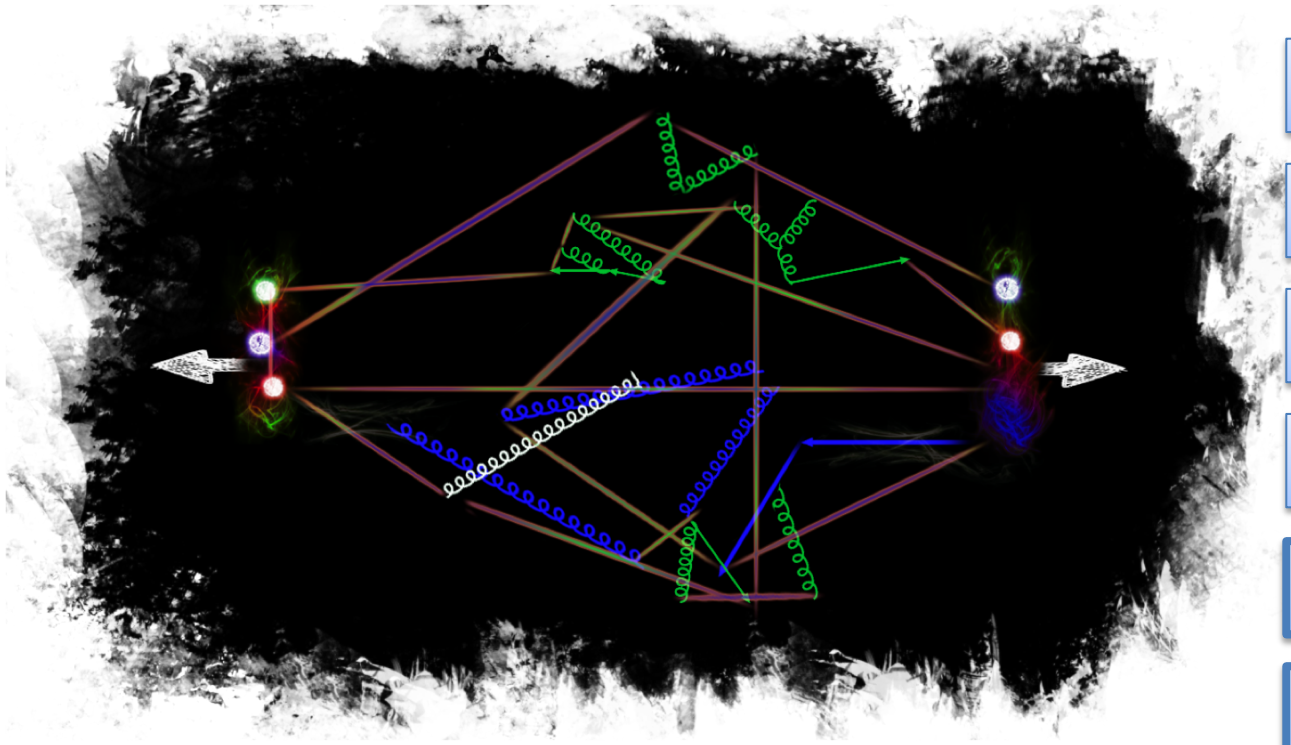
Initial state radiation (ISR)

Final state radiation (FSR)

Additional parton interactions included

Multiple interactions allowed to have **ISR** and **FSR**

A proton-proton collision for PYTHIA



Parton momenta: p.d.f.

Multiple interactions (MPI)

Initial state radiation (ISR)

Final state radiation (FSR)

Color (re)connection (CR)

Hadronization, decays

Final Partons of the Event connected via **color confinement** strings and **hadrons are created + decayed**

Multiple string hadronization: non-trivial, many approaches