Heavy Ions & Jets

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Goals for today and tomorrow

- **Heavy ion physics**: what is it, why do we study it, how is it relevant to EIC
- **How do we study the QGP?** What have we learned?
- **Jets basics**: what are they and how do they develop in vacuum? What do they look like?
- **Application of jets**: Why do we love them & how do we use it in various contexts to learn the physics we are after?

Part 1: Heavy-Ions

Goals for this part

- **Heavy ion physics**: what is it, why do we study it, how is it relevant to EIC
- **How do we study the QGP?** What have we learned?
- **Jets basics**: what are they and how do they develop in vacuum? What do they look like?
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The Strong Force and the Quark Gluon Plasma

Particles and forces of nature

Quarks & **leptons**: matter

Gluons: strong force

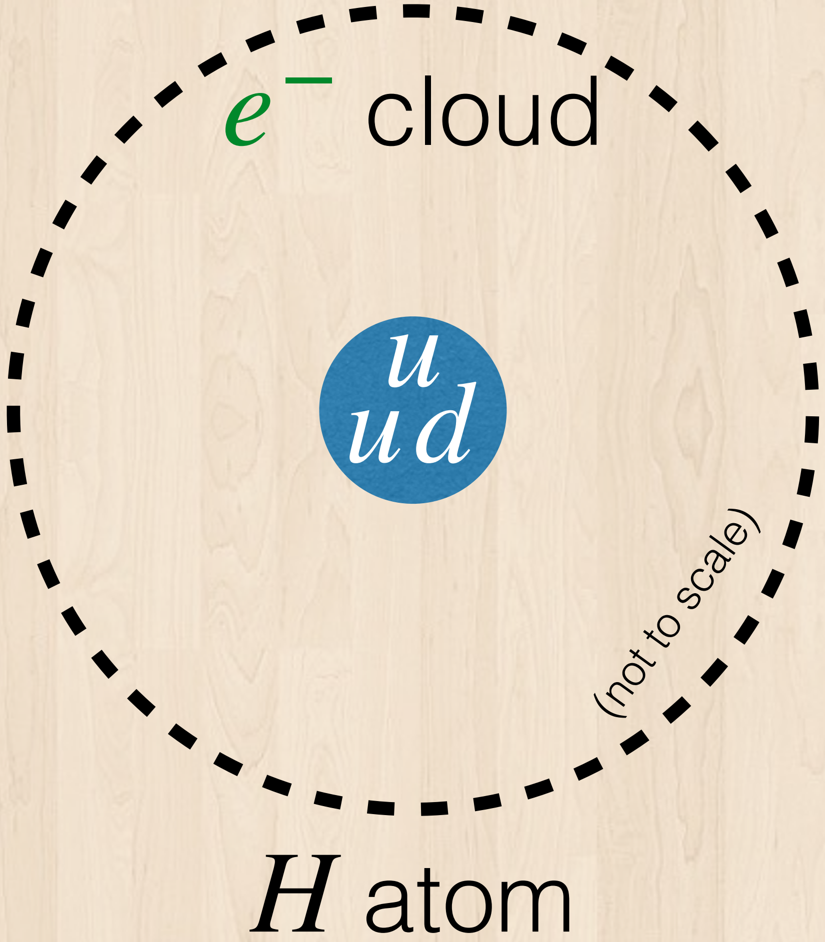
Photons: electromagnetic

Z/W bosons: weak force

Higgs boson: rest mass

Strength: **Strong** >>>> **electromagnetic** > **weak**

Strong force and QCD



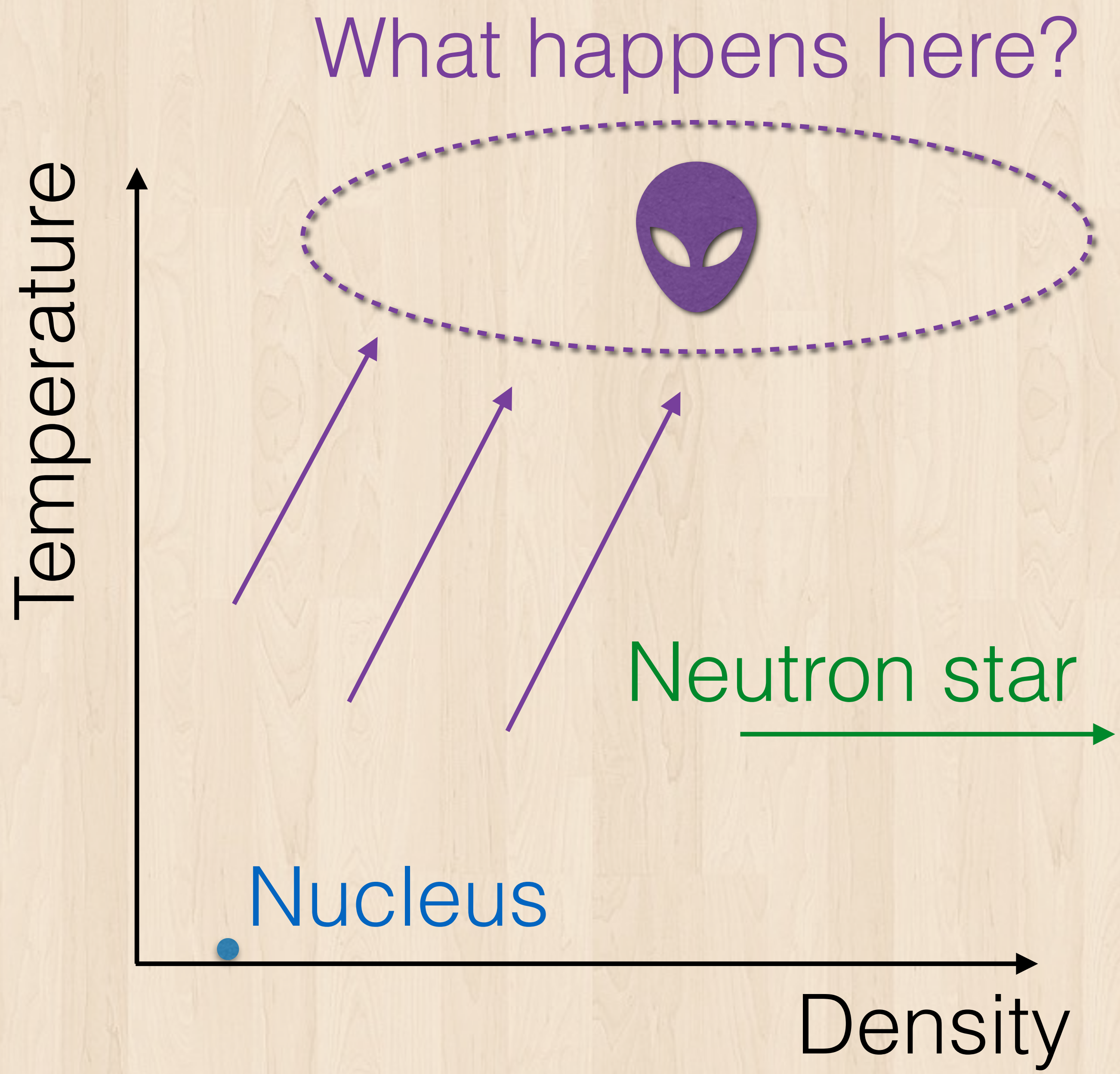
Strong force theorized as quantum chromodynamics (QCD)

Highly successful

Asymptotic freedom & confinement: quarks/gluons are confined in nuclei/hadrons

Responsible for > 98% of everyday mass

Pushing boundary: extreme conditions



Many interesting places to study the strong force

For example… what happens when we compress and heat things up?

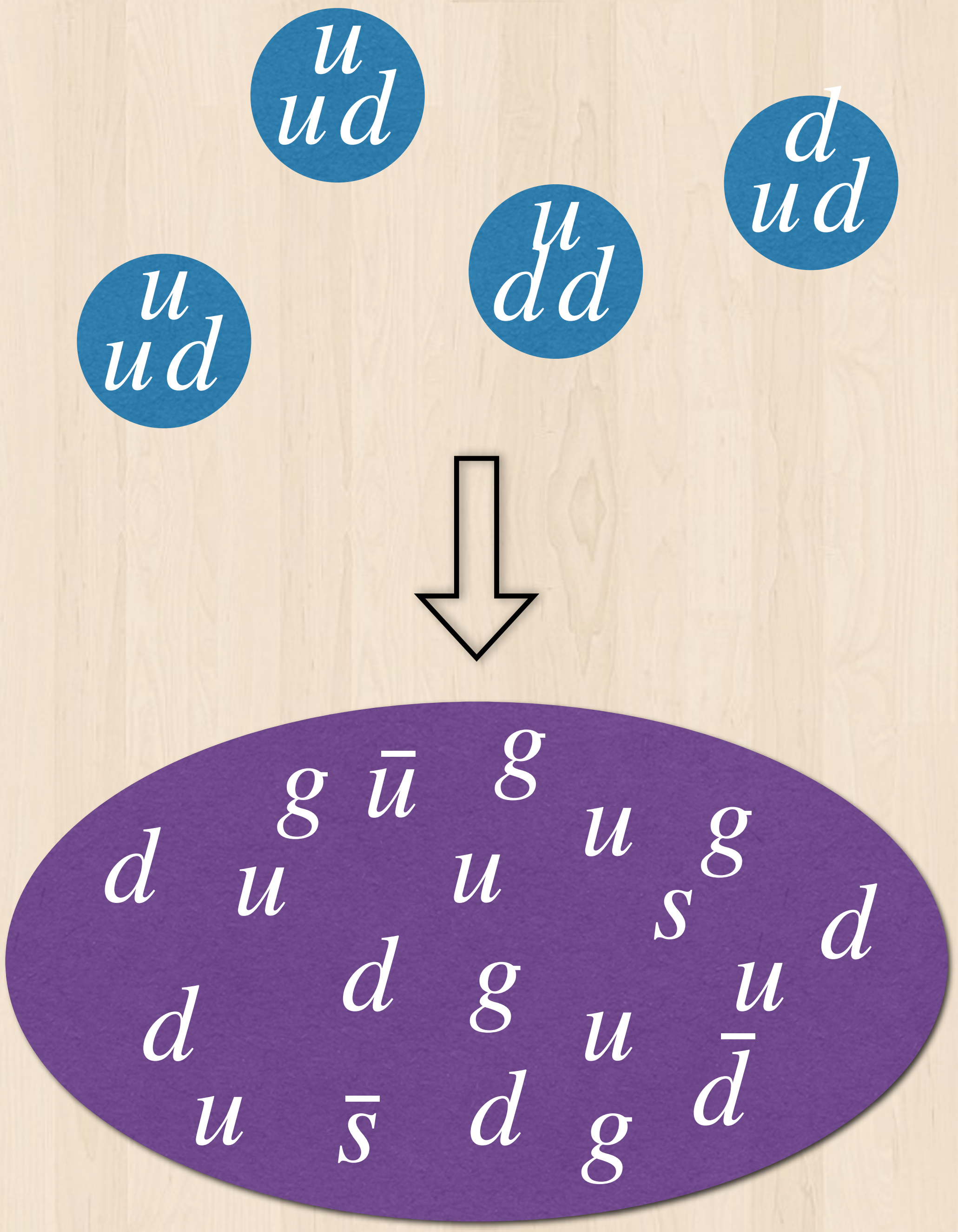
Quarks and gluons no longer confined

Quarks and gluons can move outside of the boundary of nucleus

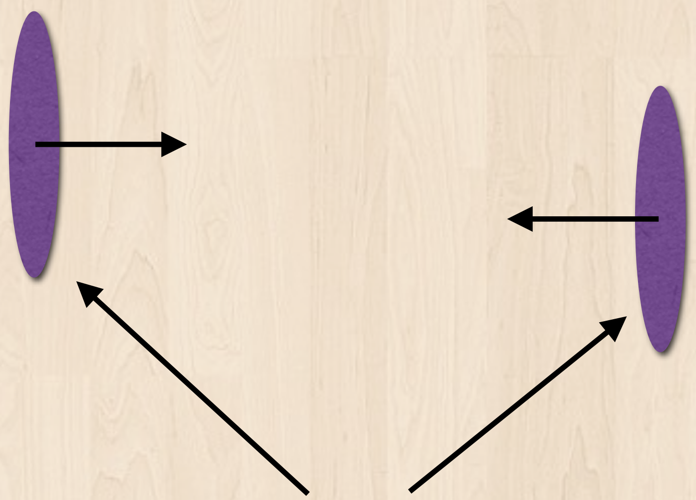
“Quark gluon plasma”

State of matter ~$10^{-6}s$ after the big bang

Can we recreate this in lab?



Heavy-ion collisions

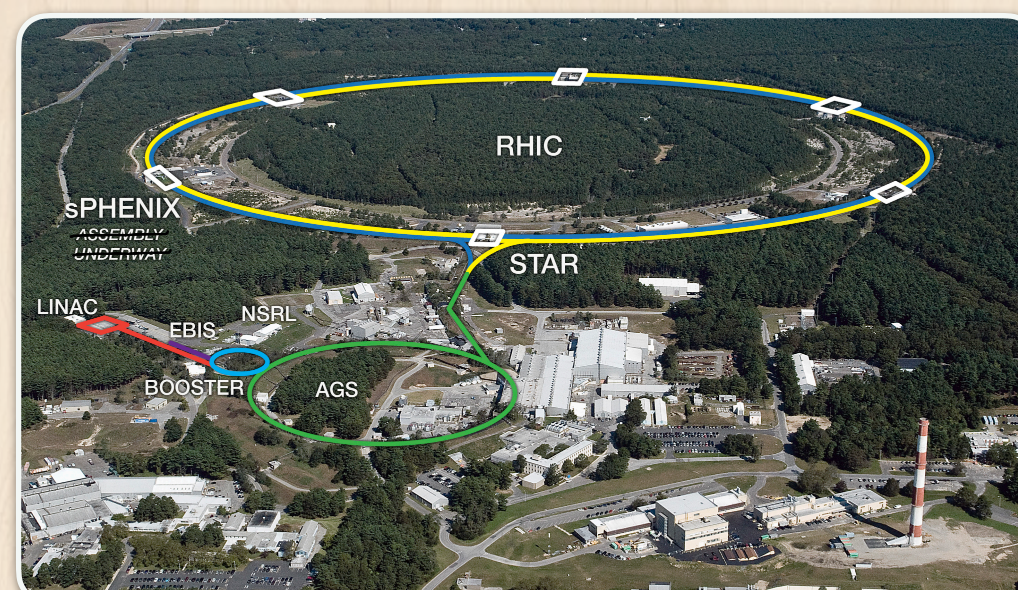


e.g. Pb/Au/Xe/… ion

Accelerate heavy ions to extreme speed and collide!

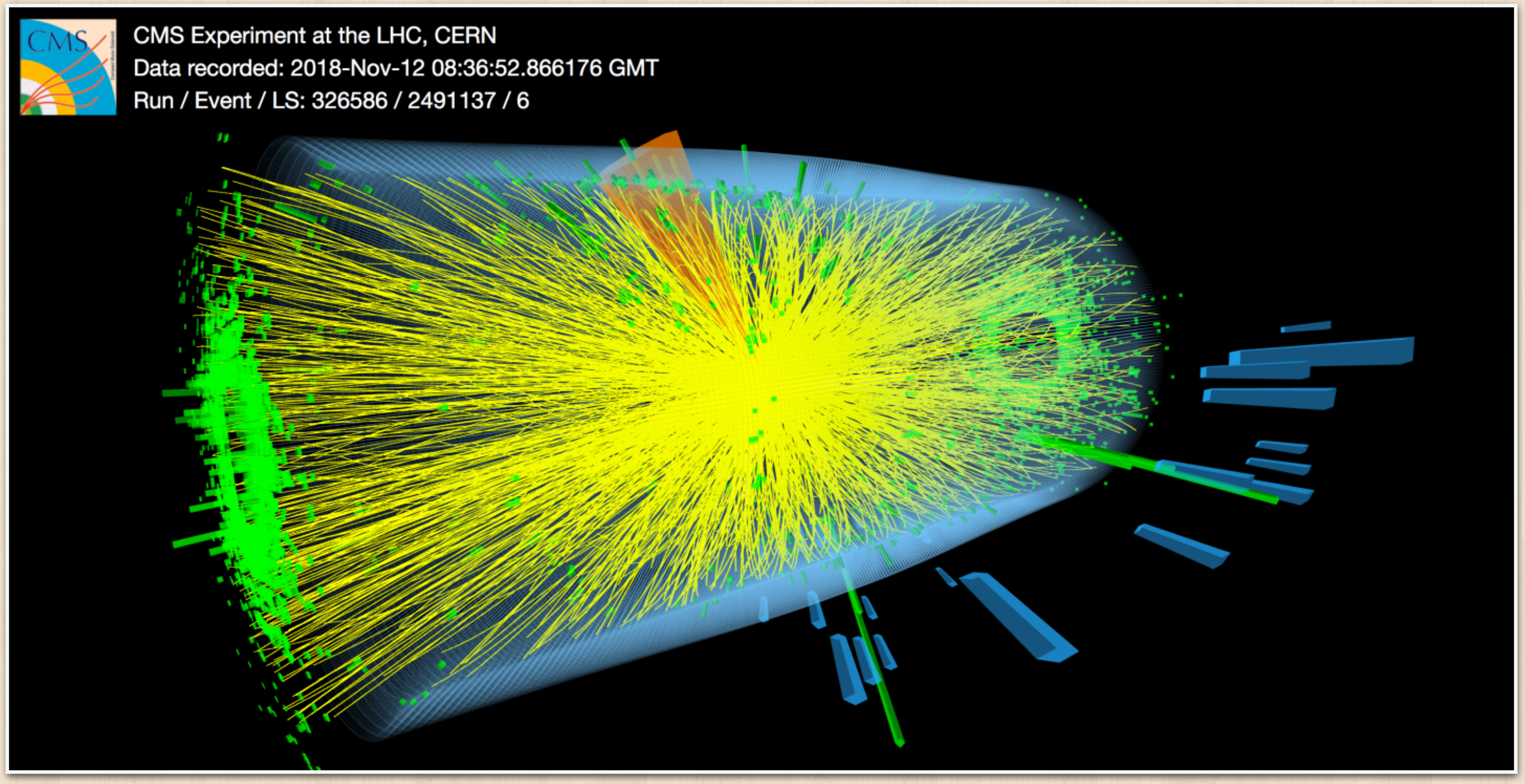
> 99.99999% speed of light
(Lorentz γ up to ~2700)

LHC, CERN, Geneva



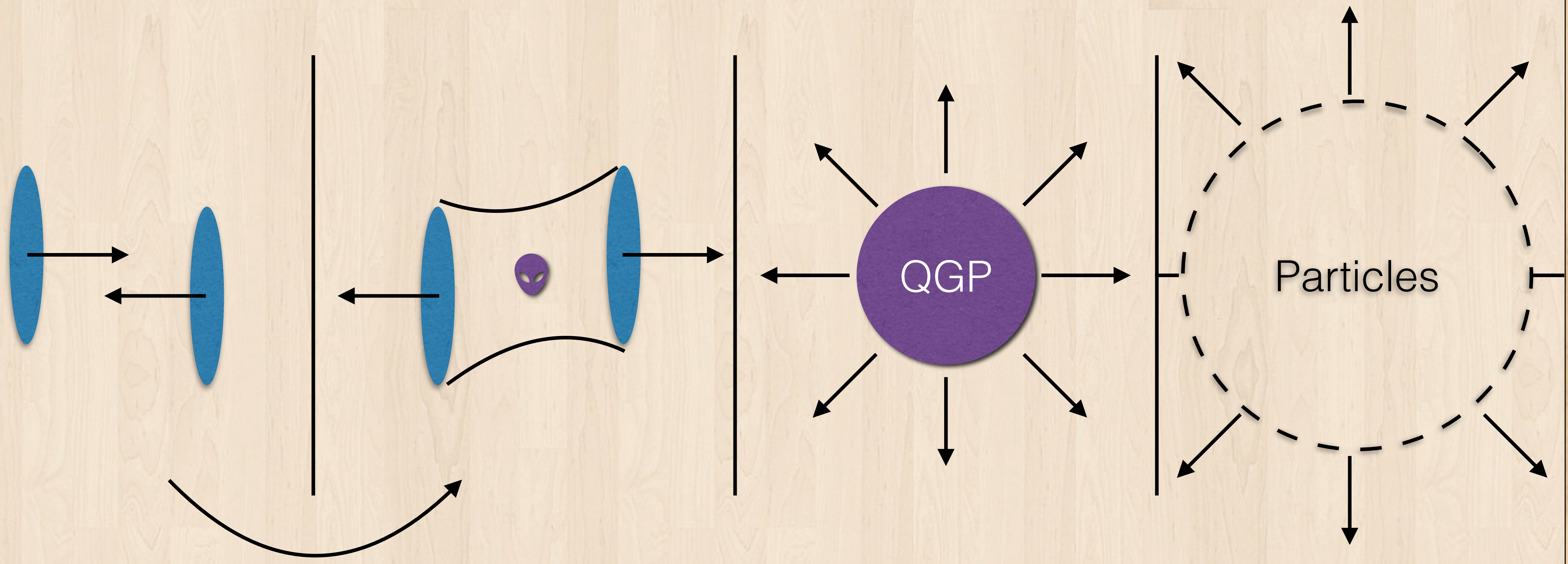
RHIC, BNL, New York

Heavy-ion collisions



Head-on collision. Huge amount of particles created

What happens after collision?



Dumps energy into the field

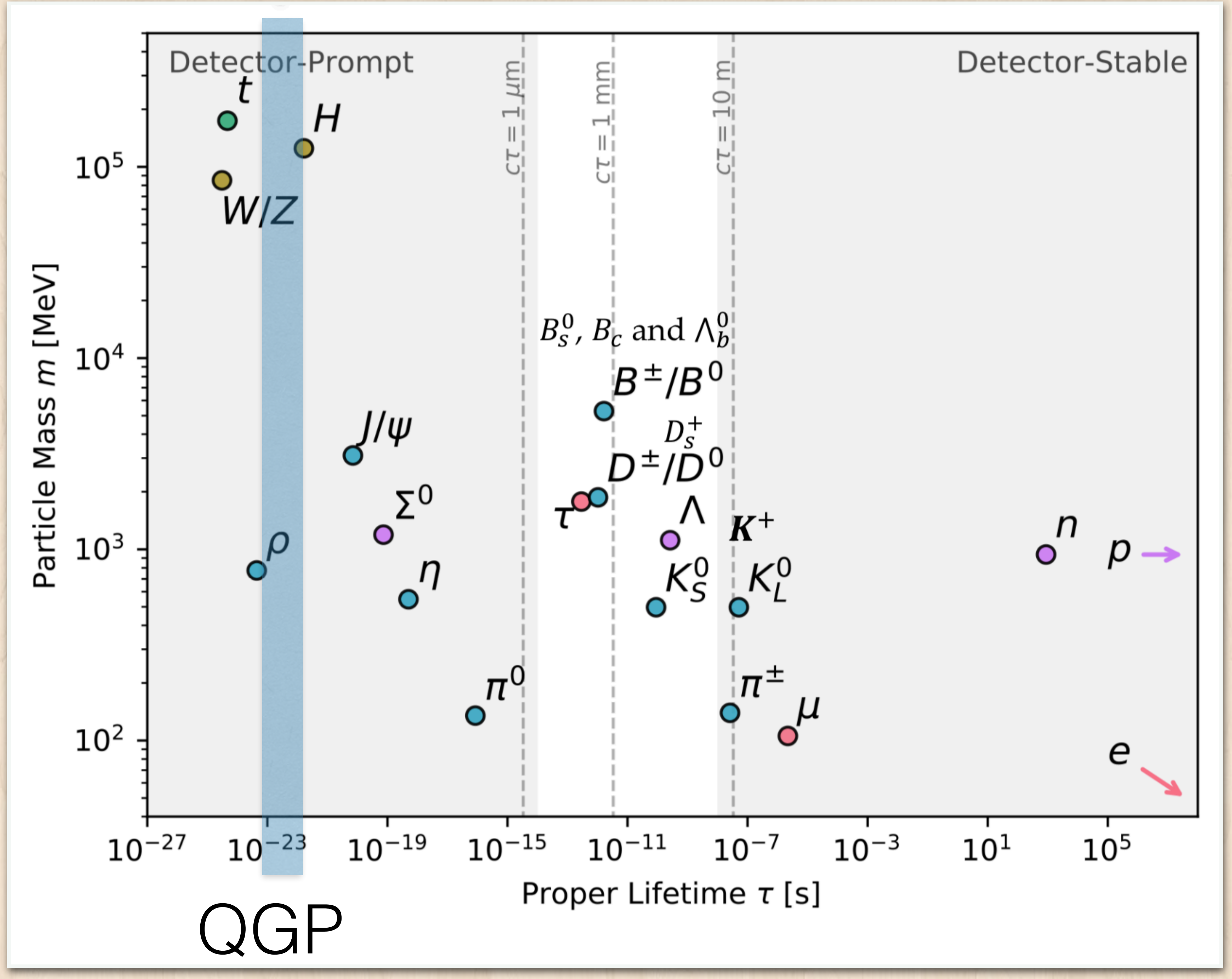
Expansion of the plasma

Decay and cool down

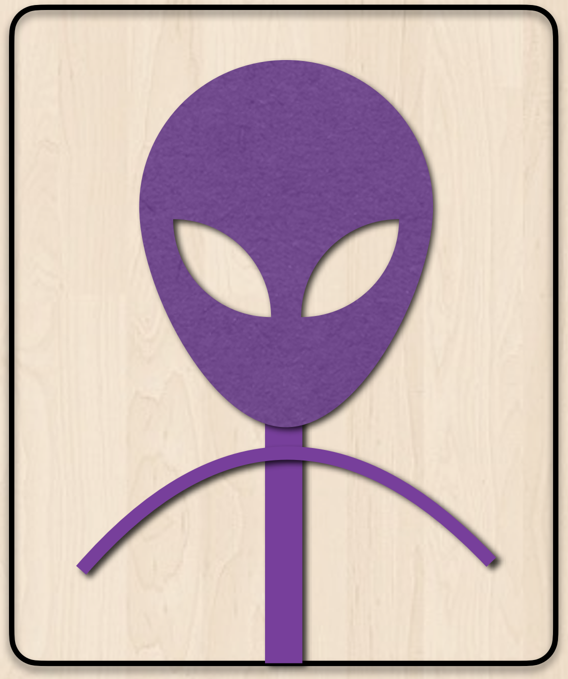
$\sim 10^{-23}s - 10^{-22}s$, or $O(10)$ fm/c

Lifetime in context

Plot stolen from Andrii



Plasma ID card



Name: quark-gluon plasma
from ion-ion collision

Nationality: collider

Lifetime: O(10) fm/c

10 fm/c $\sim 3 \times 10^{-23} s$

Temperature: 160-500 MeV / k

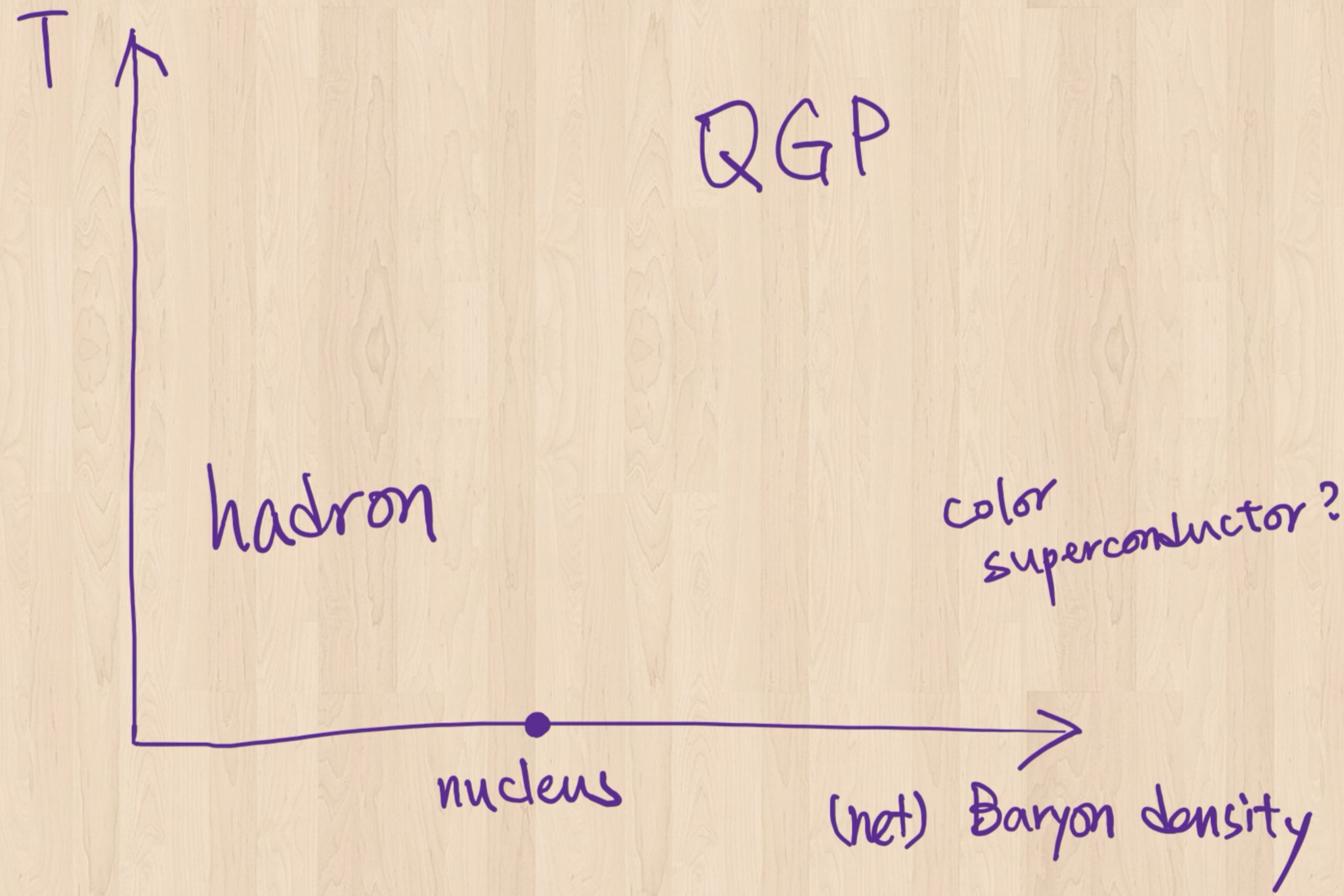
~2-5T Kelvin

Converts to particles
at around 160 MeV/k

Initial size: ~10 fm disc

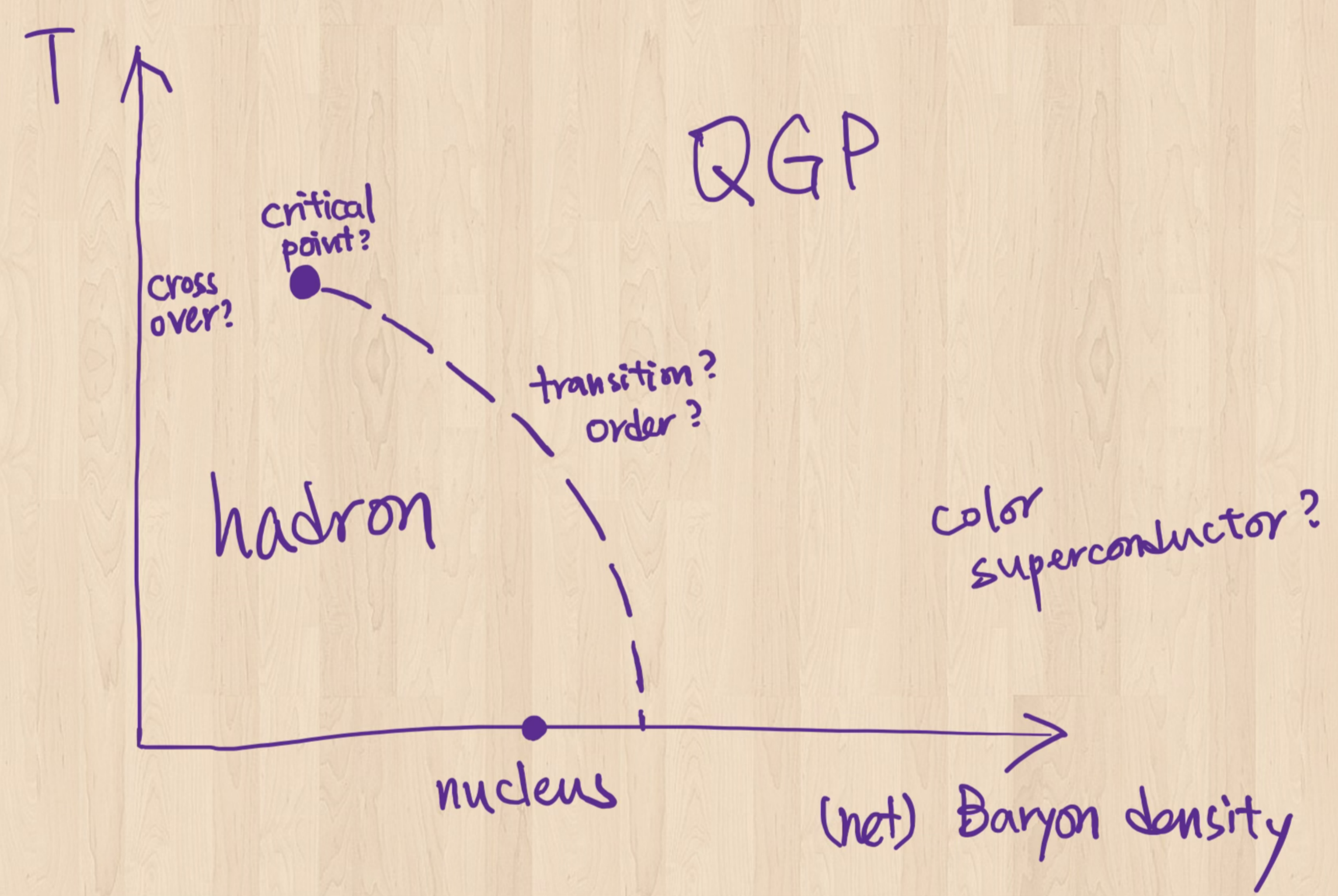
Feature: liquidy and hot-tempered

Back to QCD phase diagram



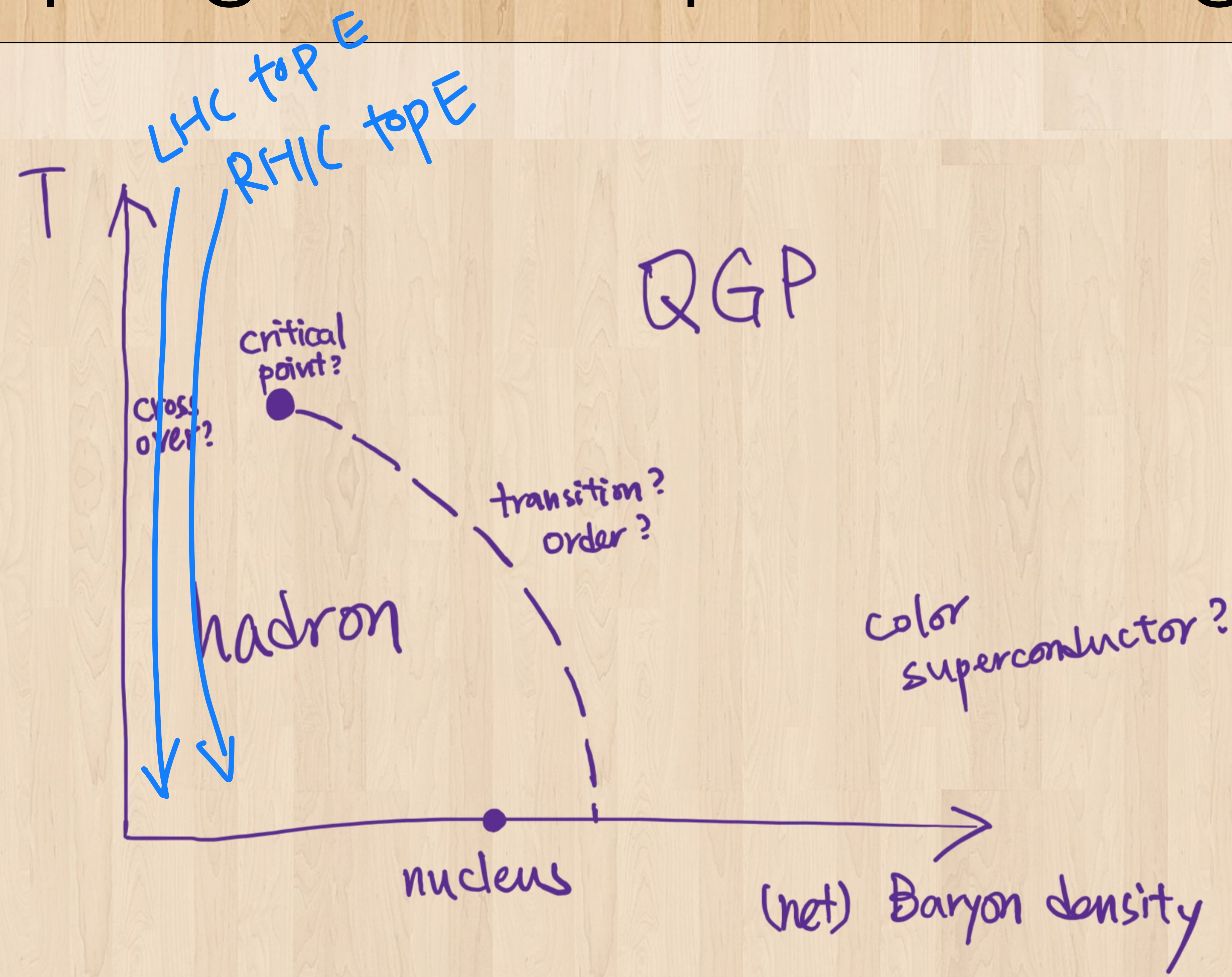
How do the two transition into each other?

Mapping out the phase diagram



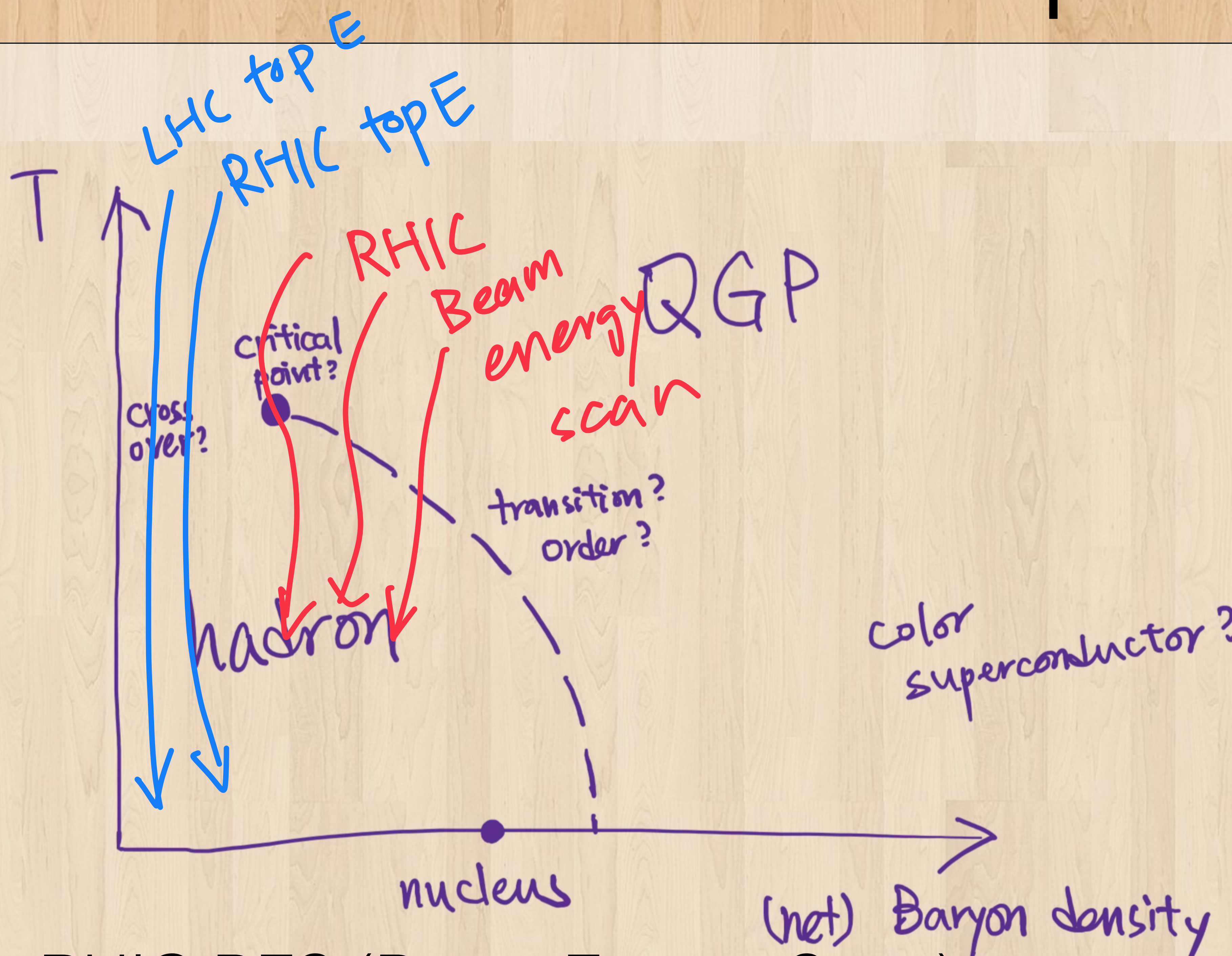
Now we see where we probe with heavy ion collisions

Mapping out the phase diagram



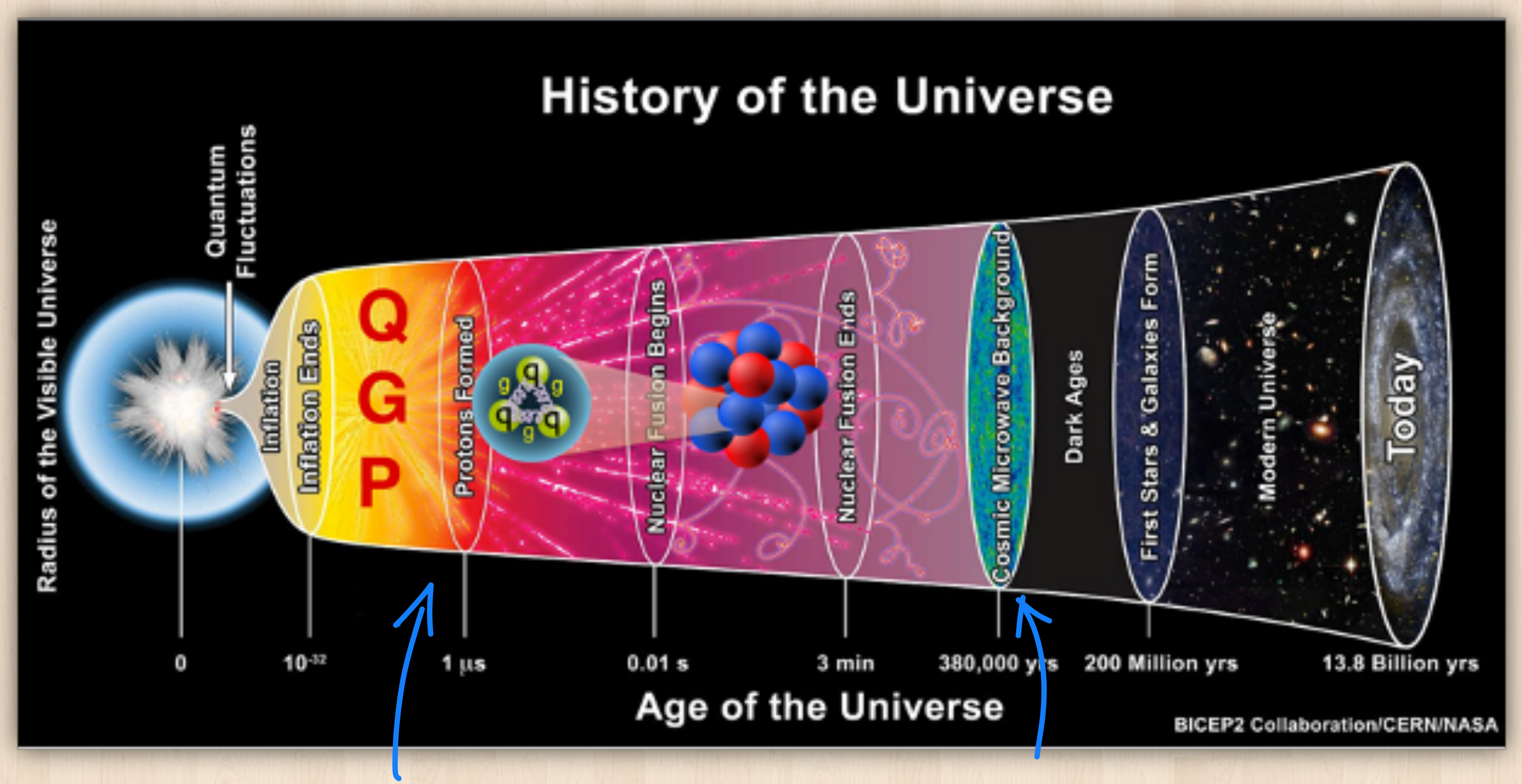
RHIC/LHC top energy mostly traces along the y axis

Search for critical point



RHIC BES (Beam Energy Scan) program maps out different lines on the diagram

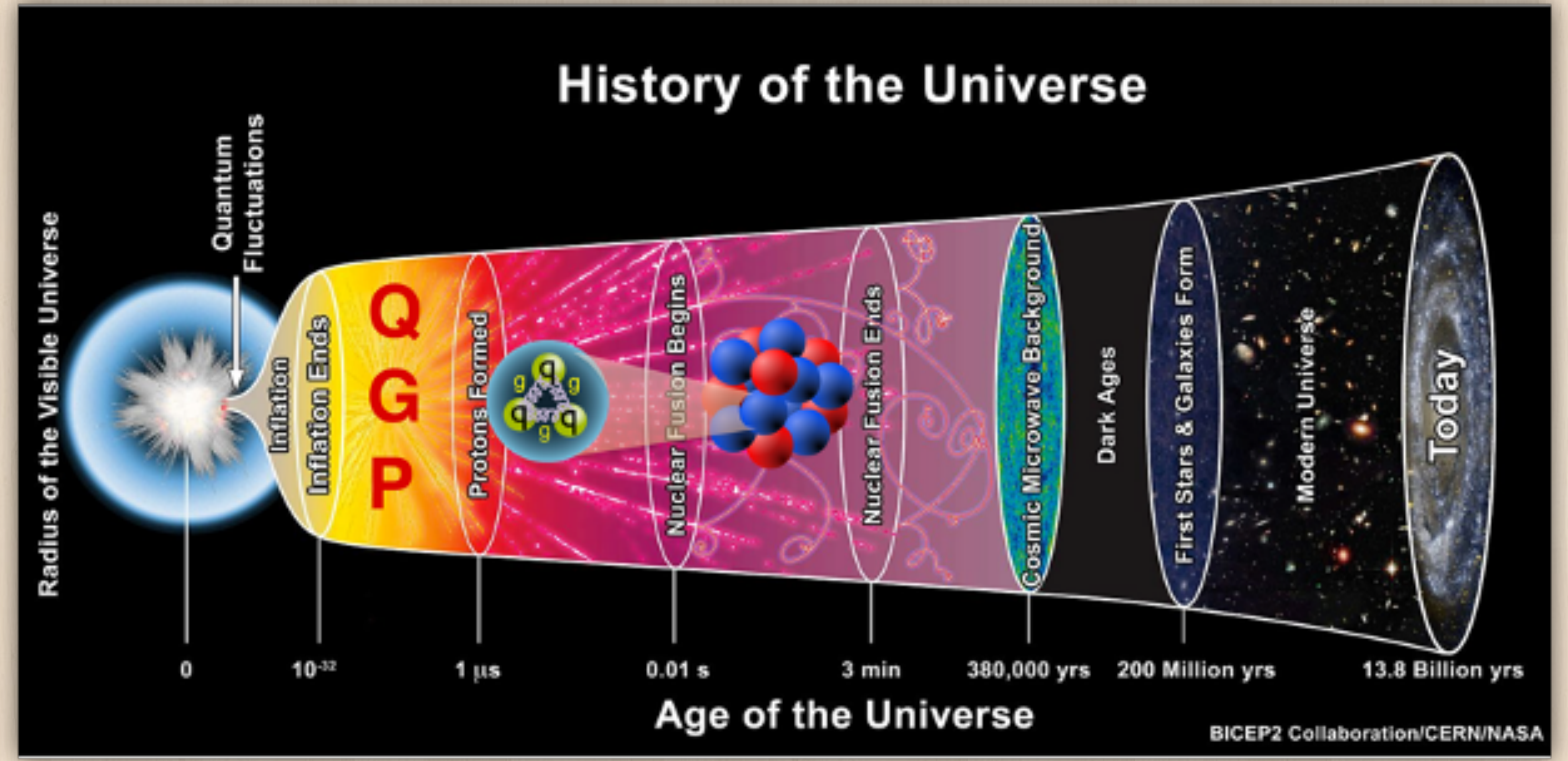
Link to early universe



QGP: $\sim 1\mu s$

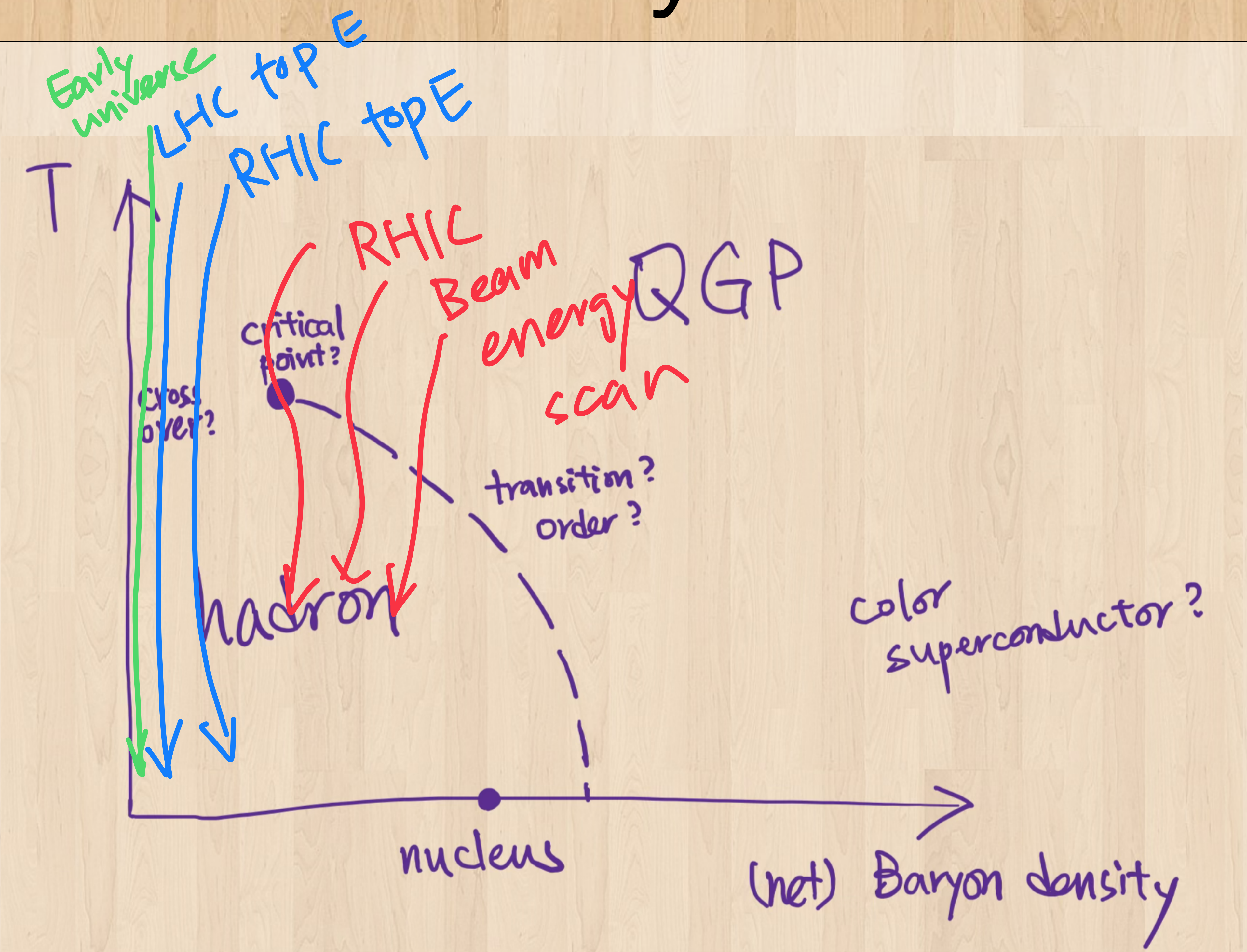
Light wall: can't see past here with light

Link to early universe



Phase transition → bubbles → potential CMB signature

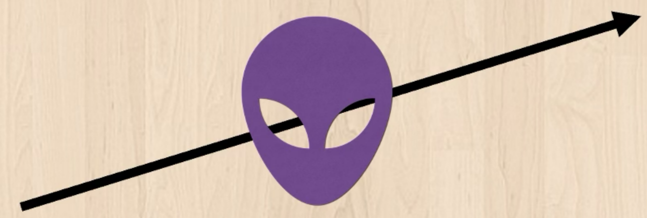
Link to early universe



Early universe: very tiny net Baryon density

How do we learn about the property of the QGP?

Generally two broad categories



Decay products of the QGP

Typical energy scale up to a few GeV

“Bulk” properties

Things going through QGP

Could have higher energy scale

Interaction with all sorts of things

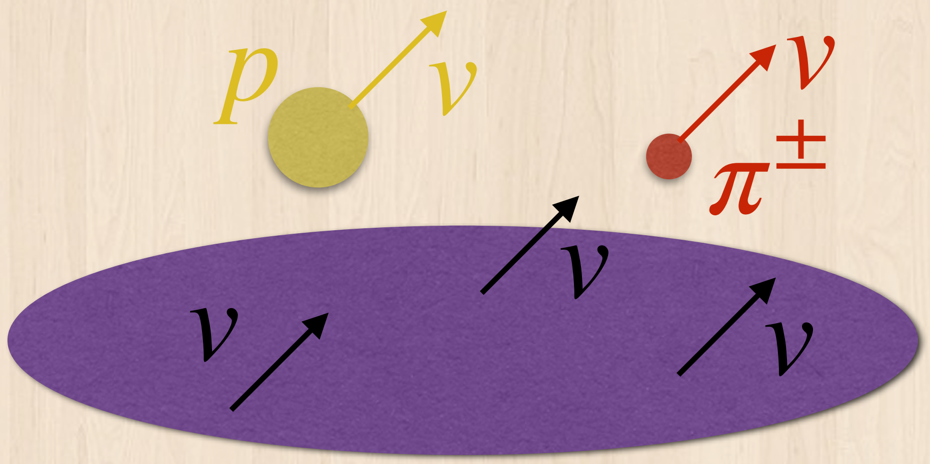
“Probes”

Let's look at the decays first

Classic evidences for the liquid phase

Analyzing the decay

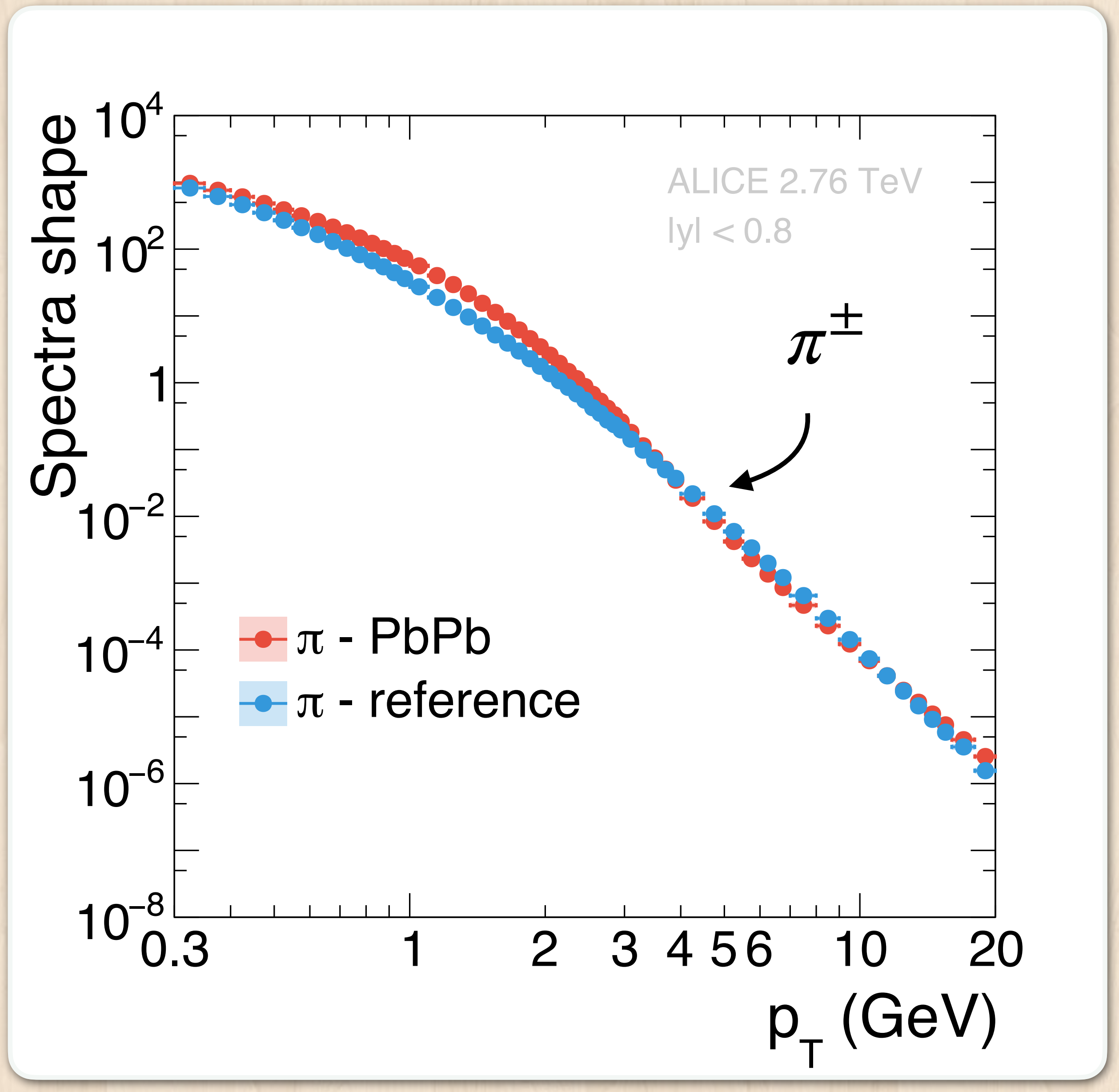
Thermodynamics => **hot quantum liquid**

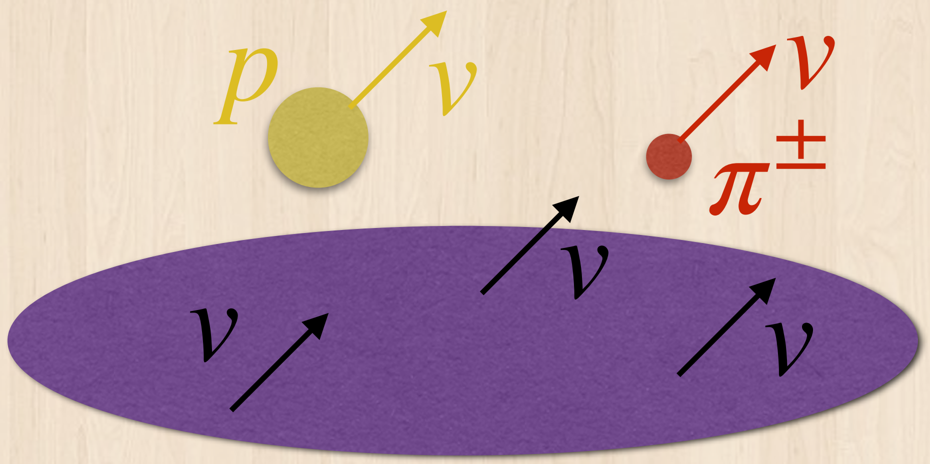


Particles get pushed by liquid

Analyzing the decay

Thermodynamics => **hot quantum liquid**





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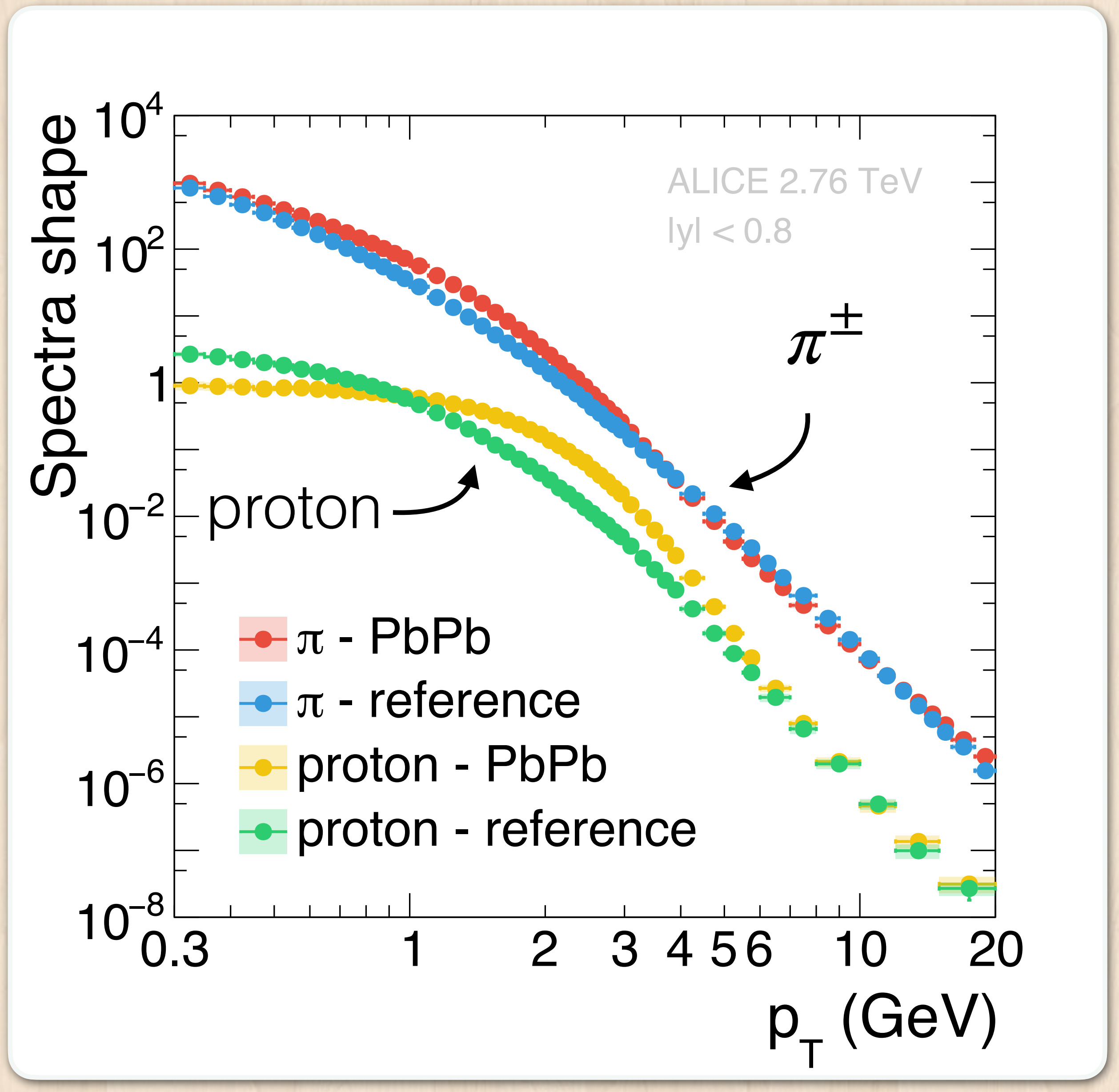

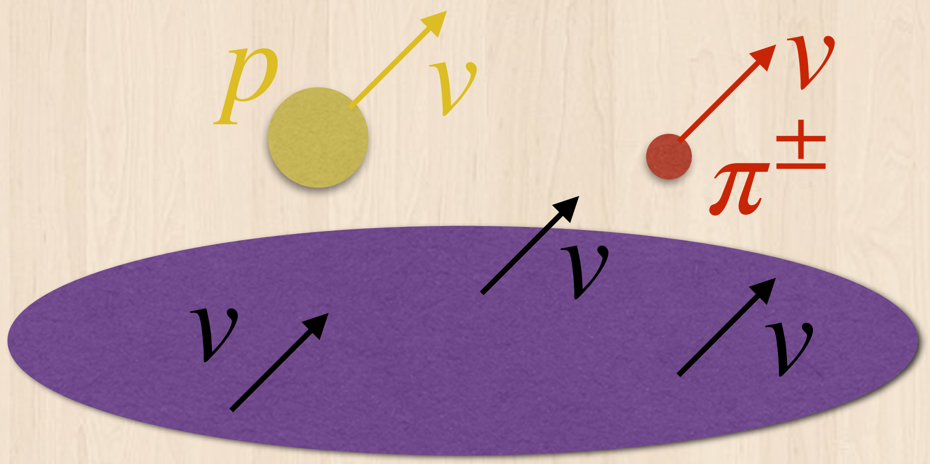

Particles get pushed by liquid

Heavier particle acquire more momentum

PLB 736 (2014) 196-207, 2014

Density gradient & pressure

- Pressure in the plasma
- Pressure gradient ~ force
- Initial geometry leads to azimuthal asymmetry

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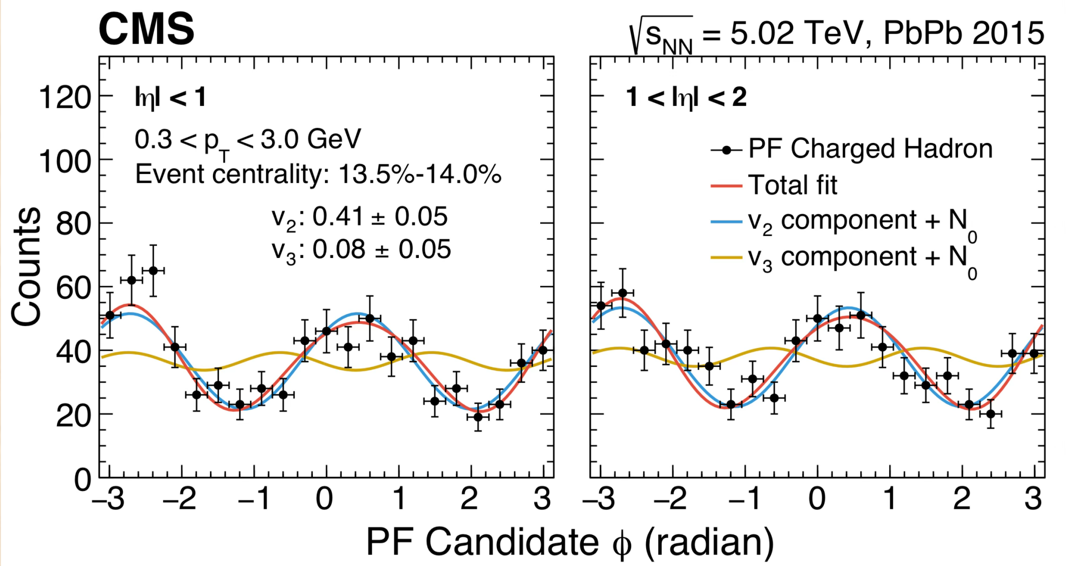
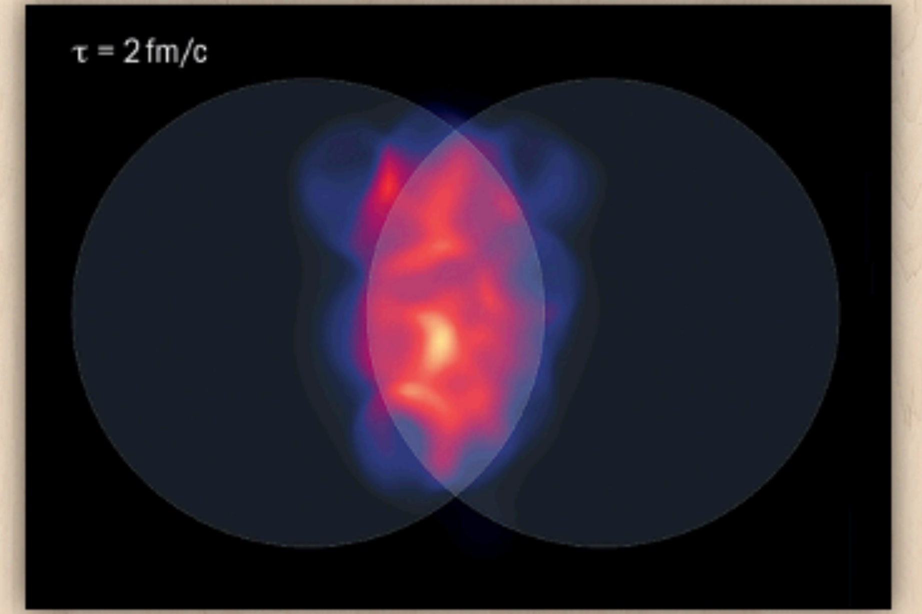
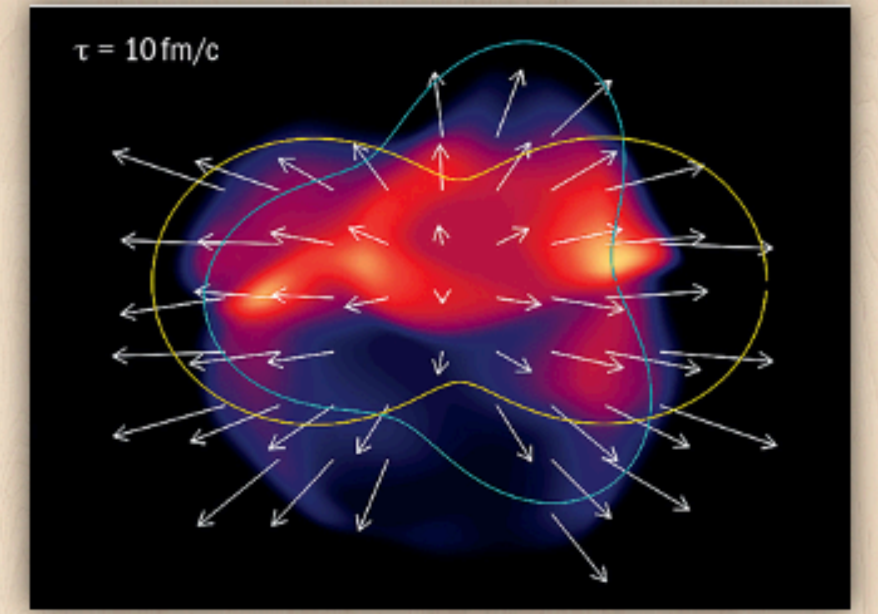


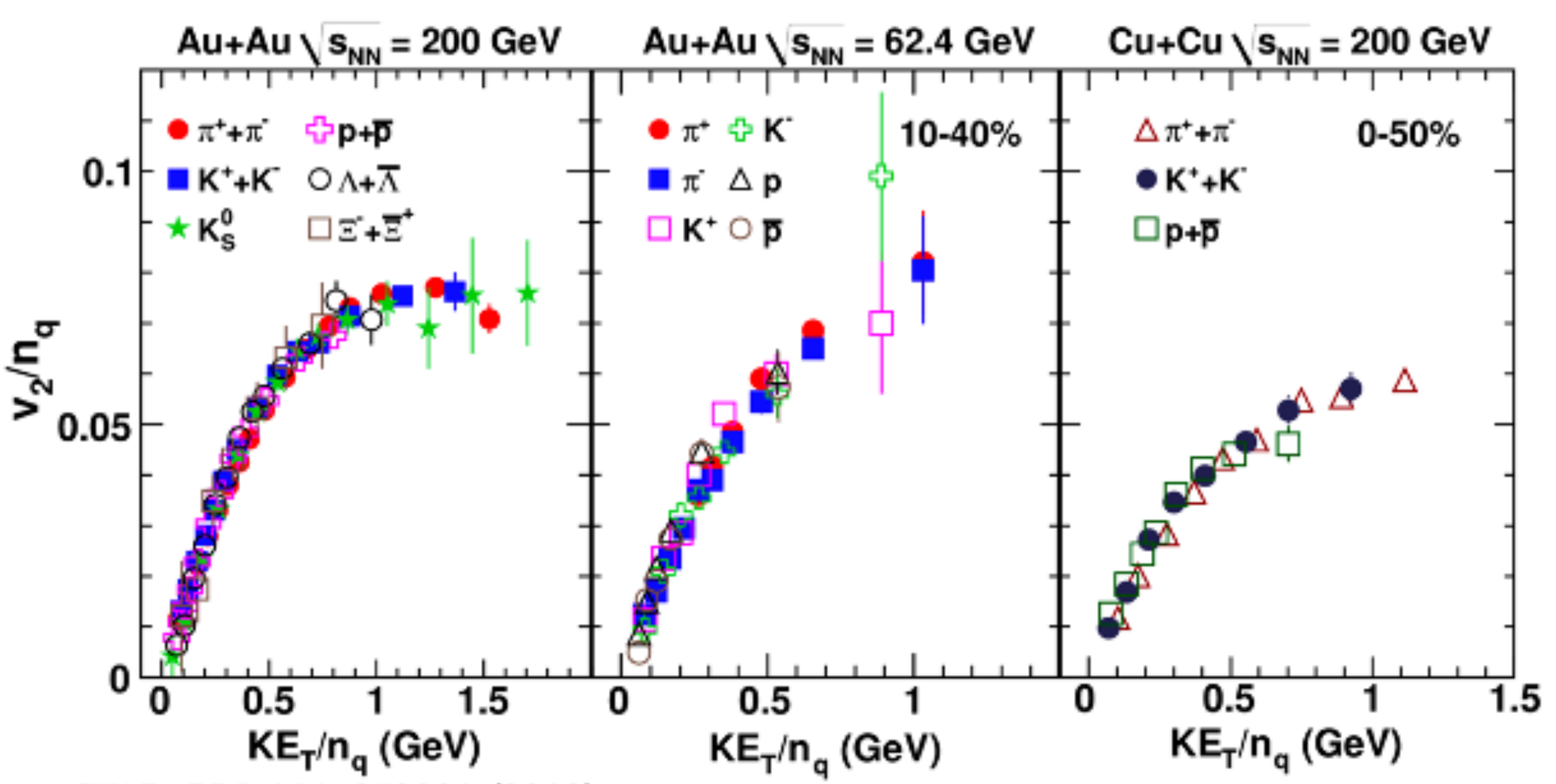




ATLAS News

Collective behavior: example

Amount of collectivity *per quark* lines up nicely across different mesons and baryons



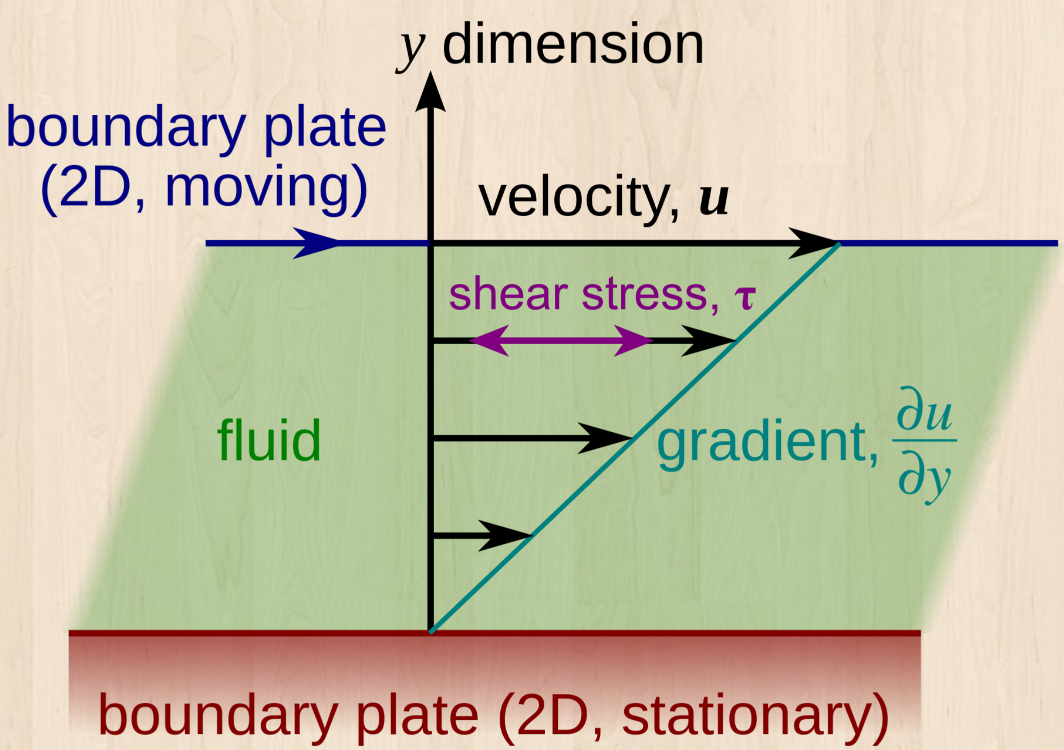
STAR, PRL 111, 052301 (2013)

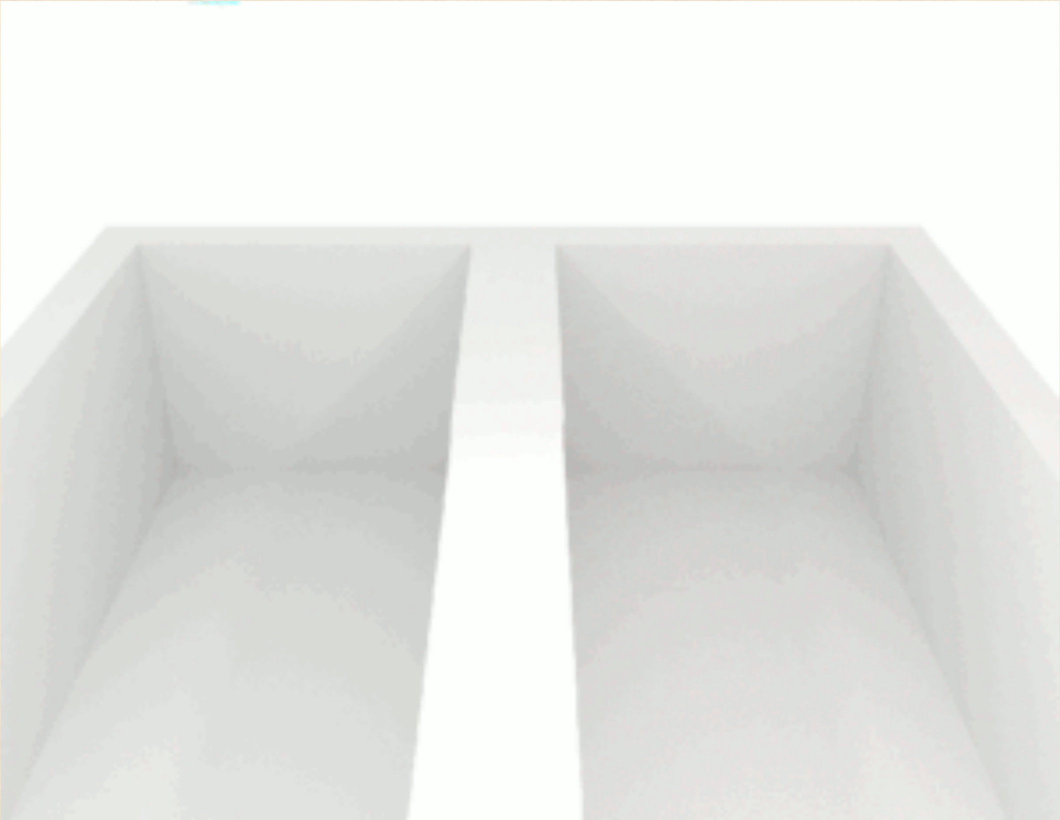
Quarks are the things that are "flowing"

Viscosity

Shear viscosity: resistance across layers of liquid

Can be inferred from (e.g.) amount of collective behavior
More viscous → asymmetry smeared out

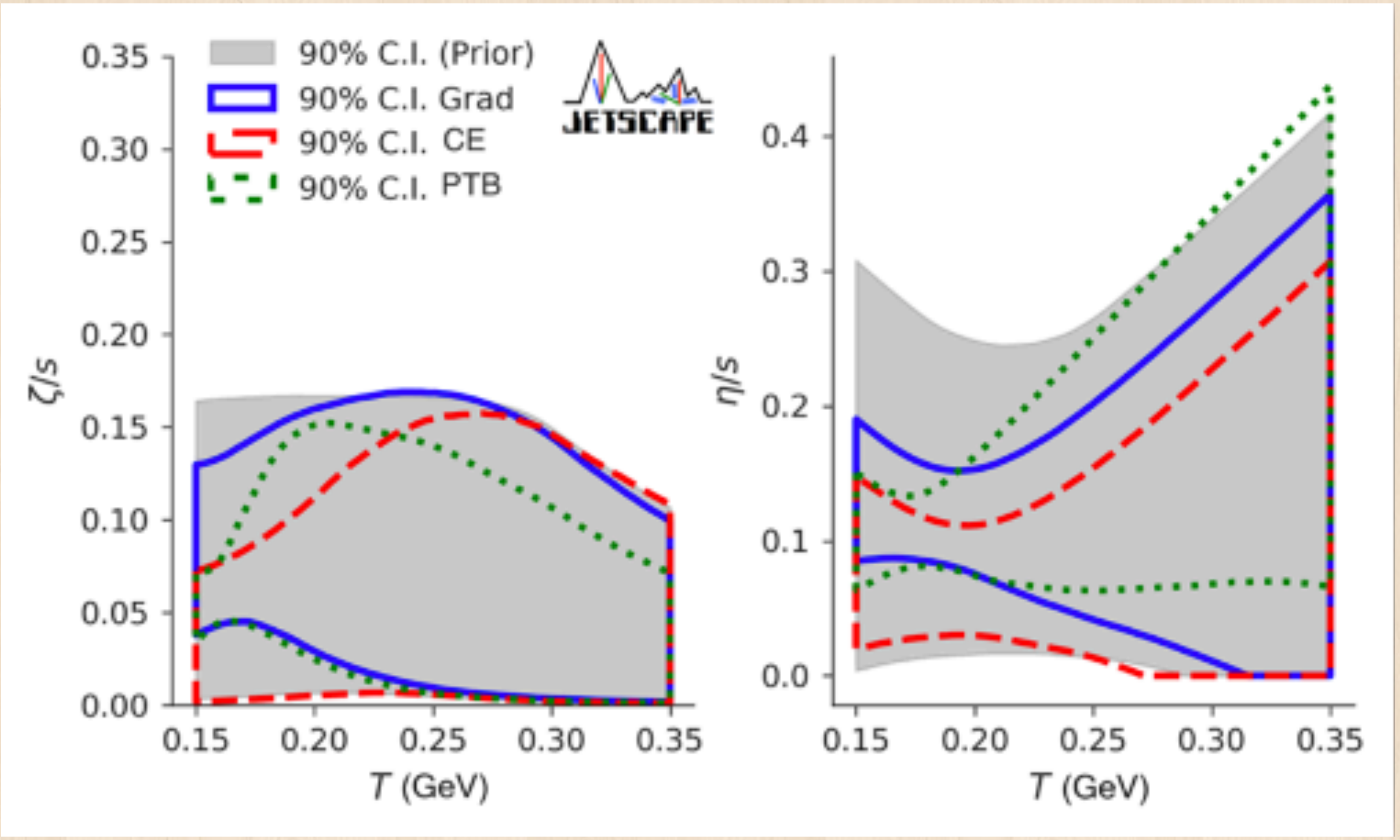




Credit: wikipedia

Extracted viscosity

Example from a Bayesian global analysis (JETSCAPE)



Bulk viscosity

Shear viscosity

Quite small!

Almost like a perfect liquid

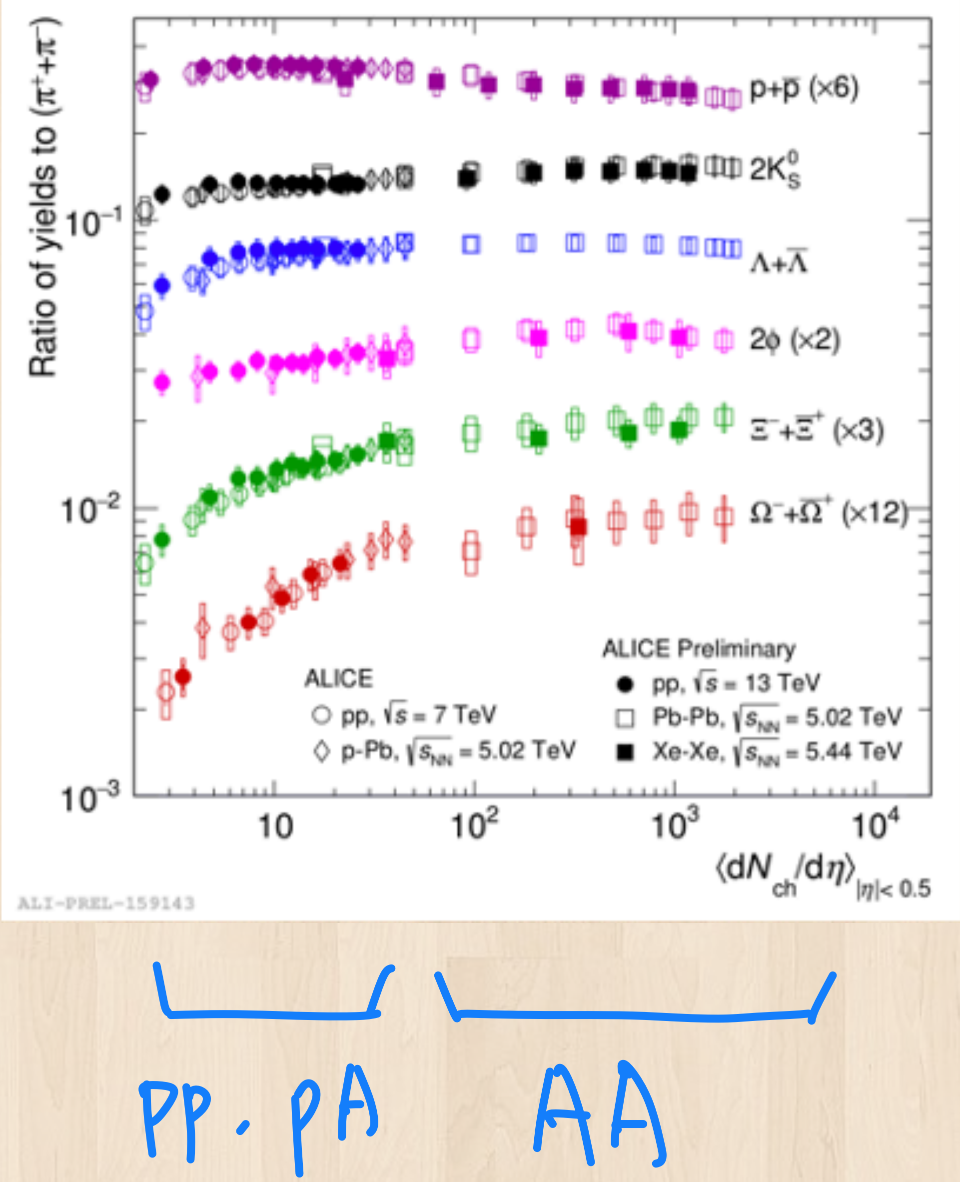
Phys. Rev. C 103, 054904

Strangeness enhancement

Another classical signature is the amount of strange particles produced

QGP temperature is high enough that we can create $s\bar{s}$ pairs

If there is QGP we expect more strange particles

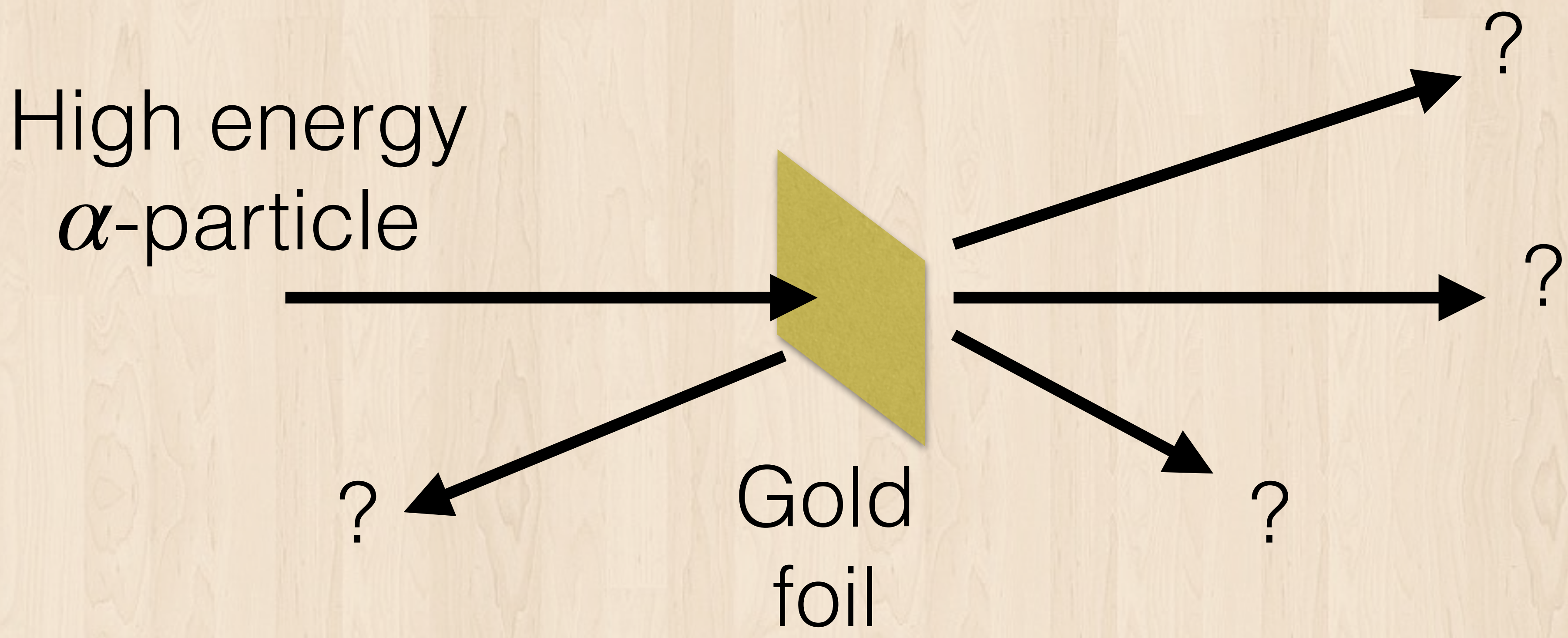


So…

- We see signs of liquid-like behavior, we have radial push, we have collective particle production
- It flows very well given the entropy with a very low specific viscosity
- We see more strange quarks created, consistent with the picture of a hot liquid with temperature same order as two strange quarks
- Let’s look at the other class of observables next

Going a step further: how do we study the structure of….things?

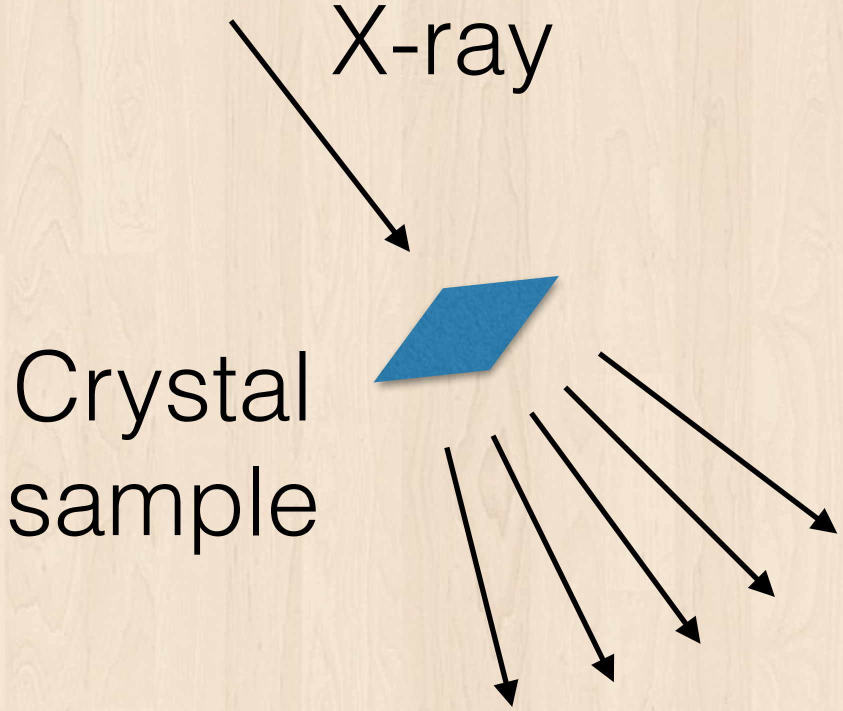
Rutherford experiment (1911)

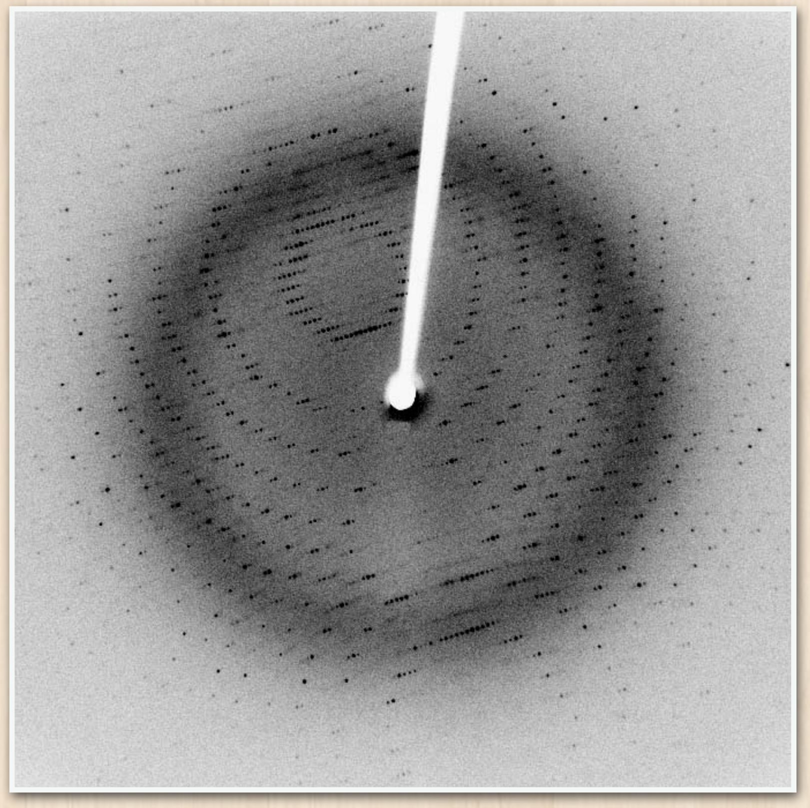


Shoot high energy particles to probe the structure

Distribution of outgoing particles tell us something about the structure of the target (the atom in this case)

X-ray on crystals



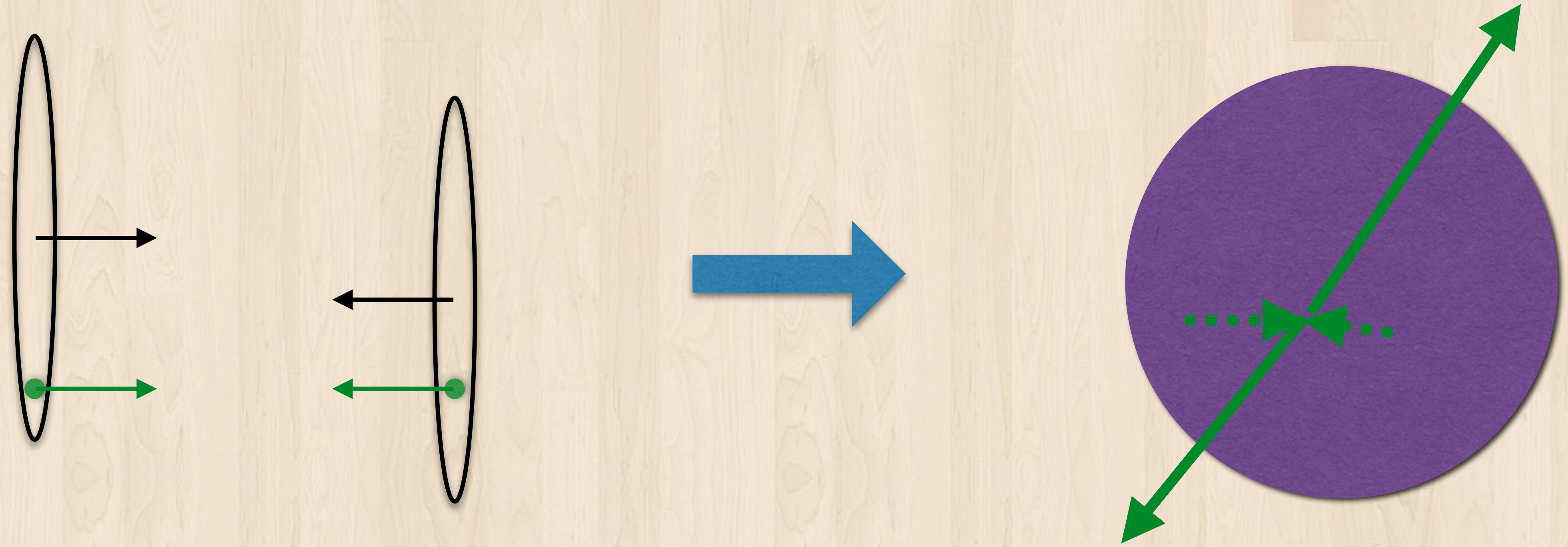


Credit: Jeff Dahl, wikipedia

Periodic nature of crystal → nontrivial interaction

Diffraction pattern tells us something about the structure

Doing “scattering”

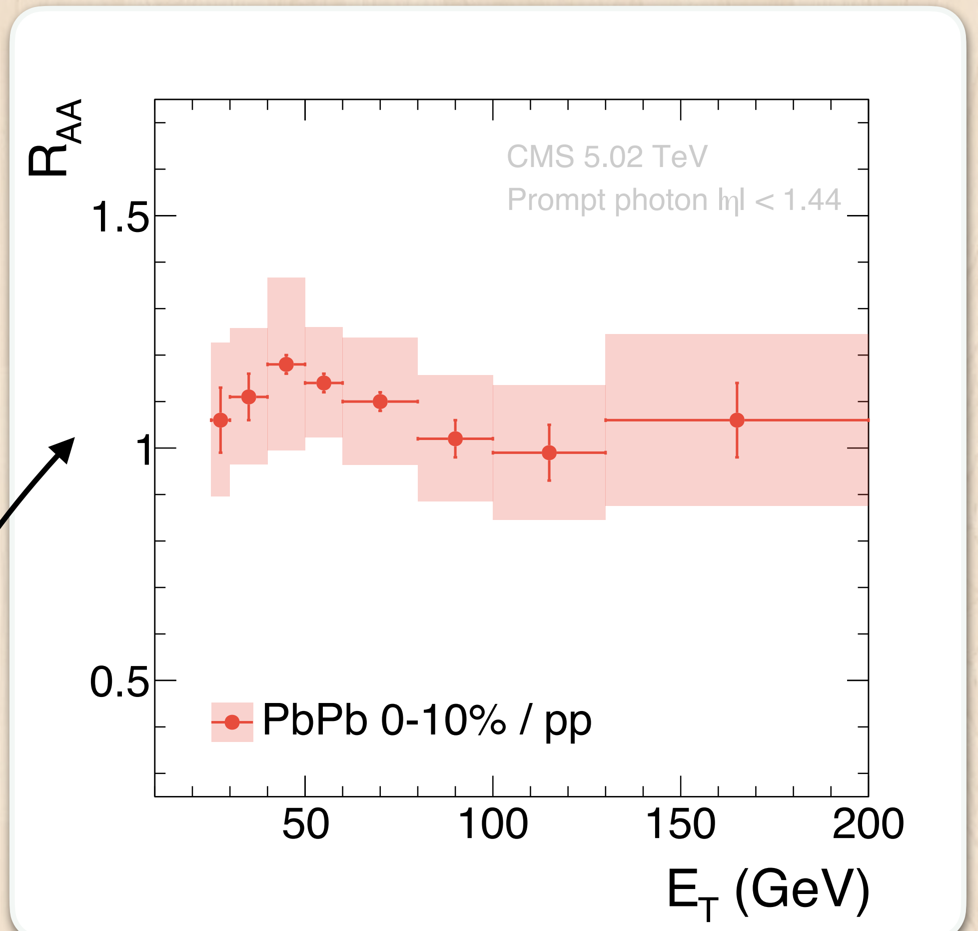


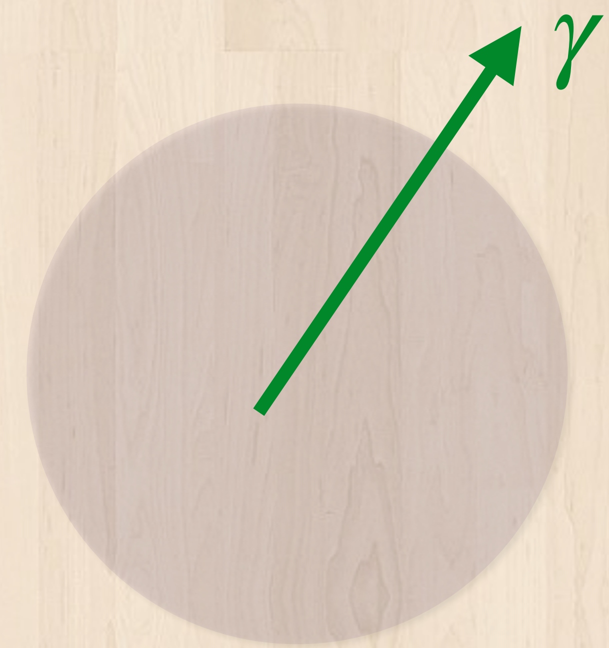
Very rarely there will be high energy particles created in the initial collision before the plasma forms

All-in-one scattering experiment prepared by nature 😎

Example: photons, leptons

(High energy) photons





~transparent

"Nuclear modification factor":

$$R_{AA} = \frac{\sigma \text{ with QGP (PbPb)}}{\sigma \text{ without QGP (reference)}} \sim 1$$

What about electrons/muons?

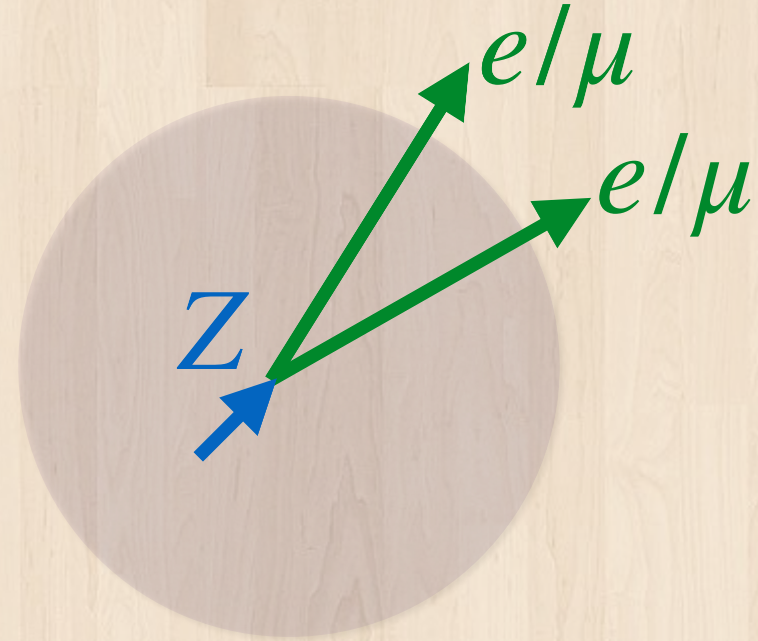
JHEP 07 (2020) 116, 2020

Z's (high energy leptons)

Z boson decay time $\sim 3 \times 10^{-25} s$

Decays before QGP is formed

What we see is the decay product



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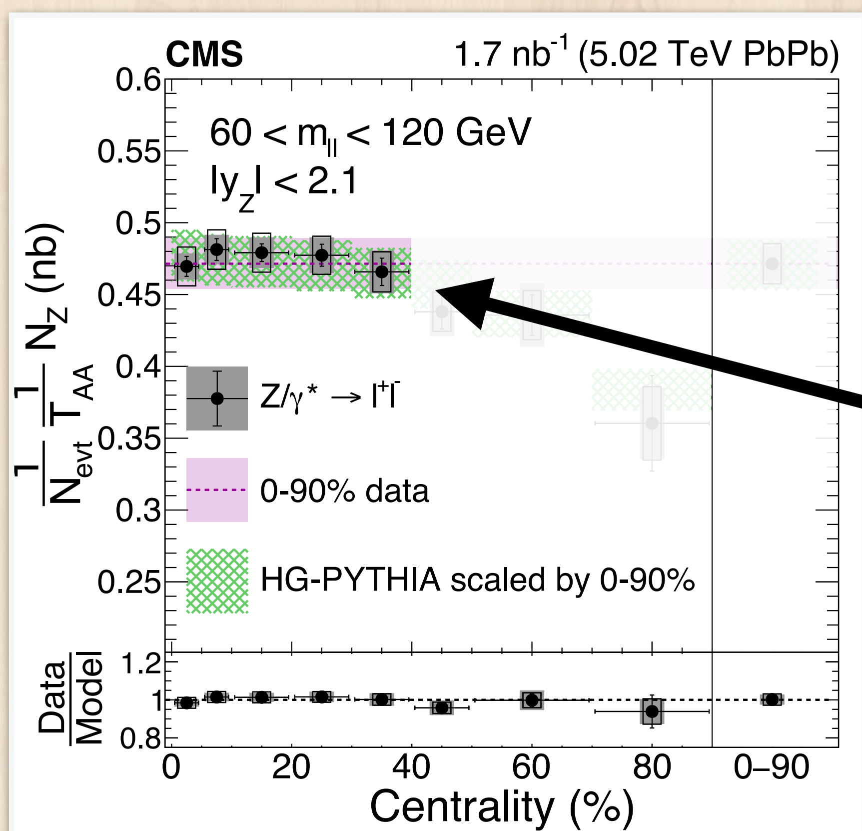


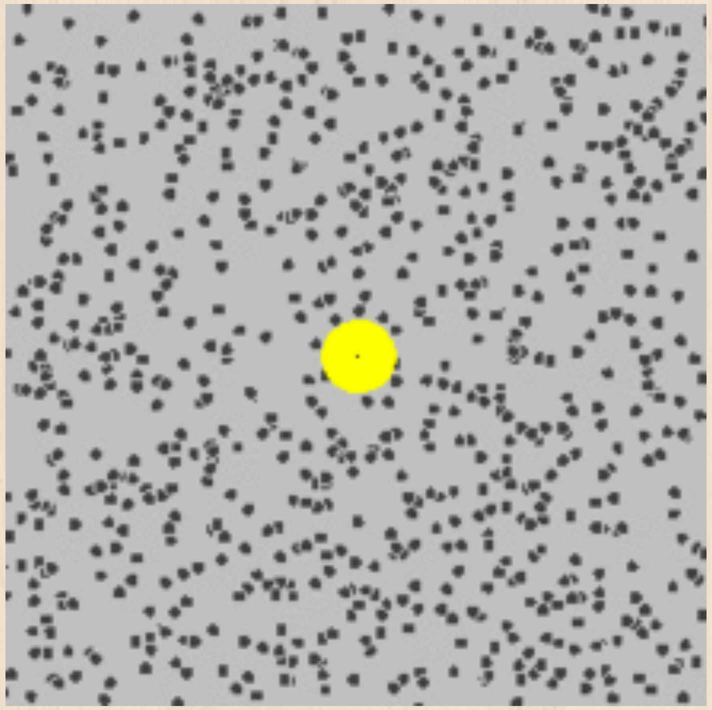
Heavy-ion data agrees with expectation from pp **collision**, even in head-on collisions

Example: heavy quarks

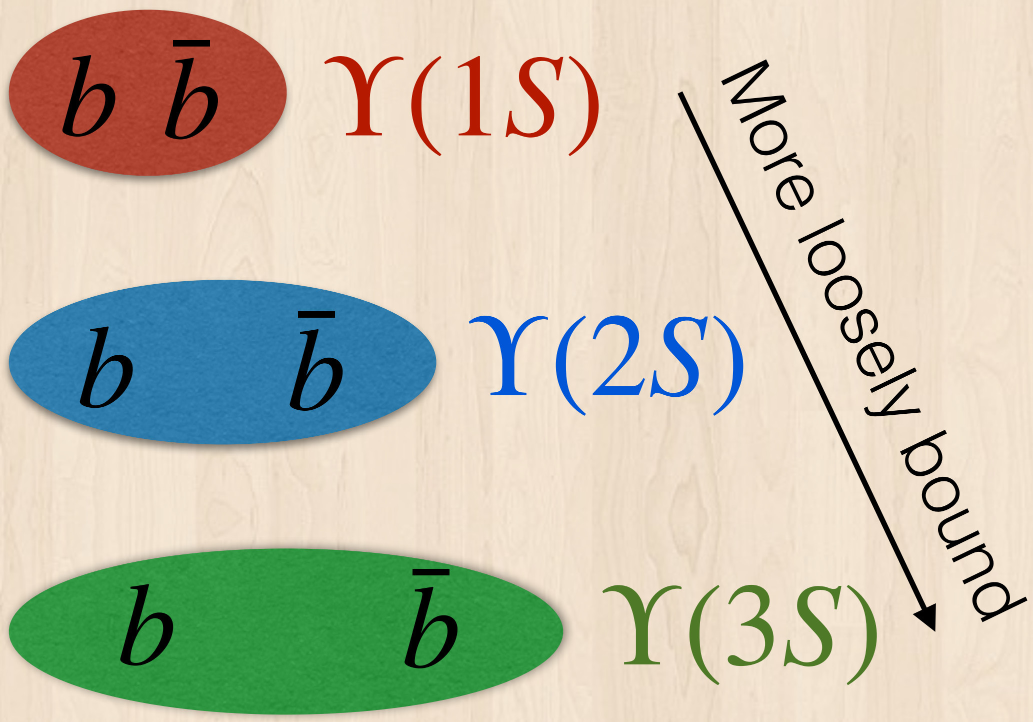
Heavy quarks (c, b)

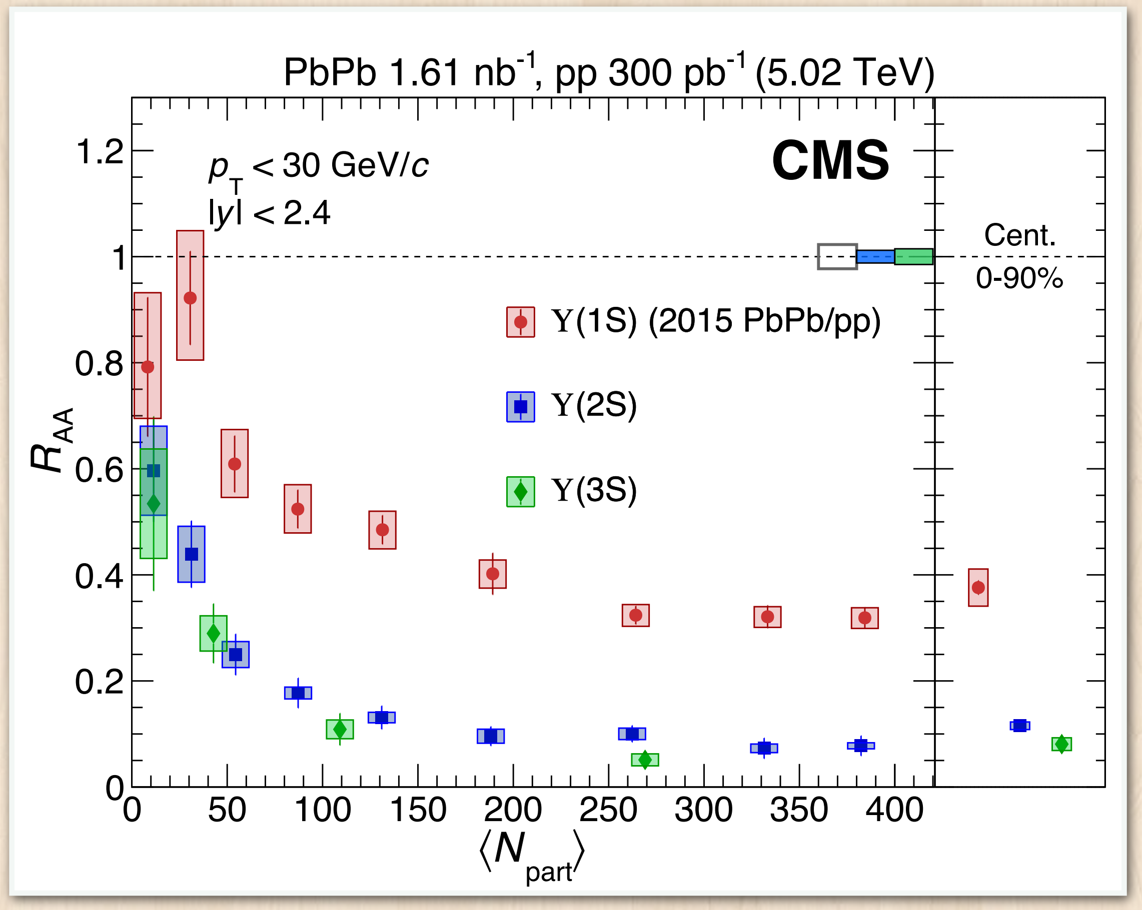
- Predominantly produced in the beginning (QGP not hot enough)
- Weak decay: decay time >> QGP lifetime
- Samples through the full QGP evolution
- Good probes for…
  - Hadronization studies
  - Quark-medium interaction & energy loss
  - Thermalization and collectivity
  - …

Wikipedia



Quarkonia (heavy $q\bar{q}$)





Different states = different binding strength

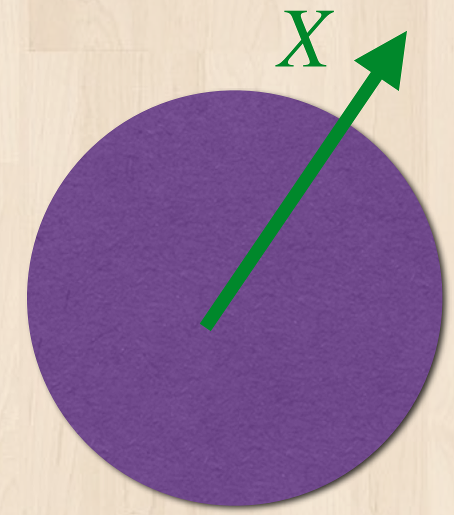
How "easy" it is for QGP to destroy it
How "easy" it is to have recombinations

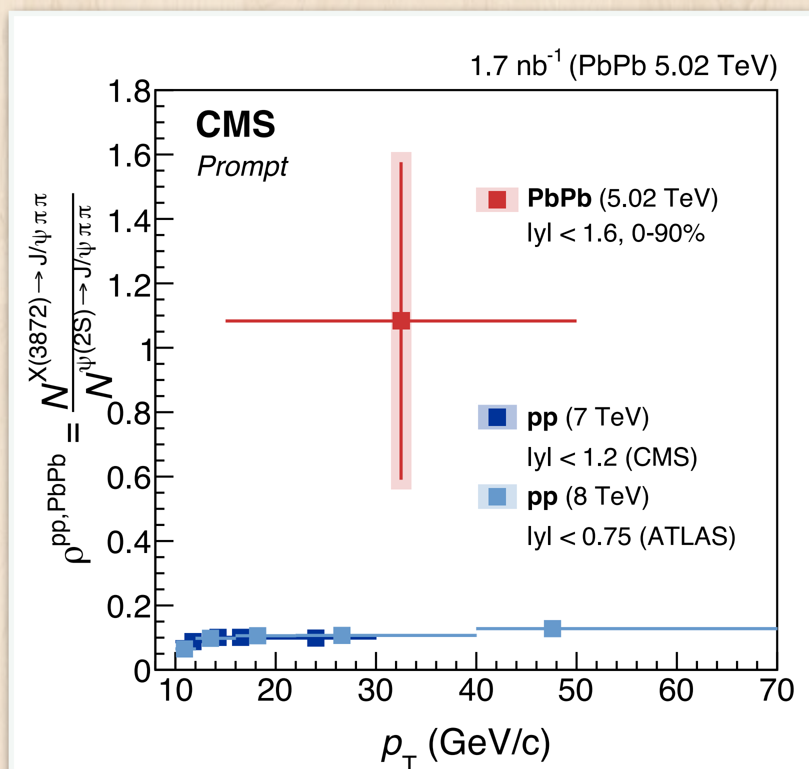
arxiv 2303.17026

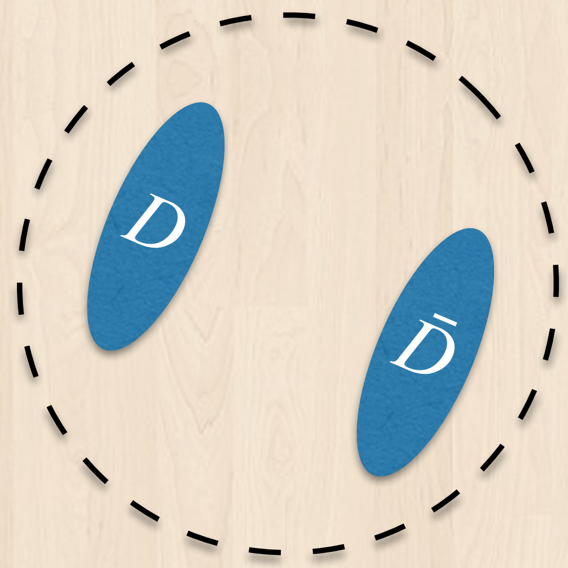
Exotic states

Related ideas but with a state with unknown origin. For example X(3872)

$$m_X \gtrsim m_{D^0} + m_{\bar{D}^0}$$







or

?

(or something else)

We use QGP to probe the X(3872)!

Phys. Rev. Lett. 128 (2022) 032001

Example: light quarks and gluons

They become jets

Stay tuned for the second half where we will talk a lot more about what we can learn from jets :)

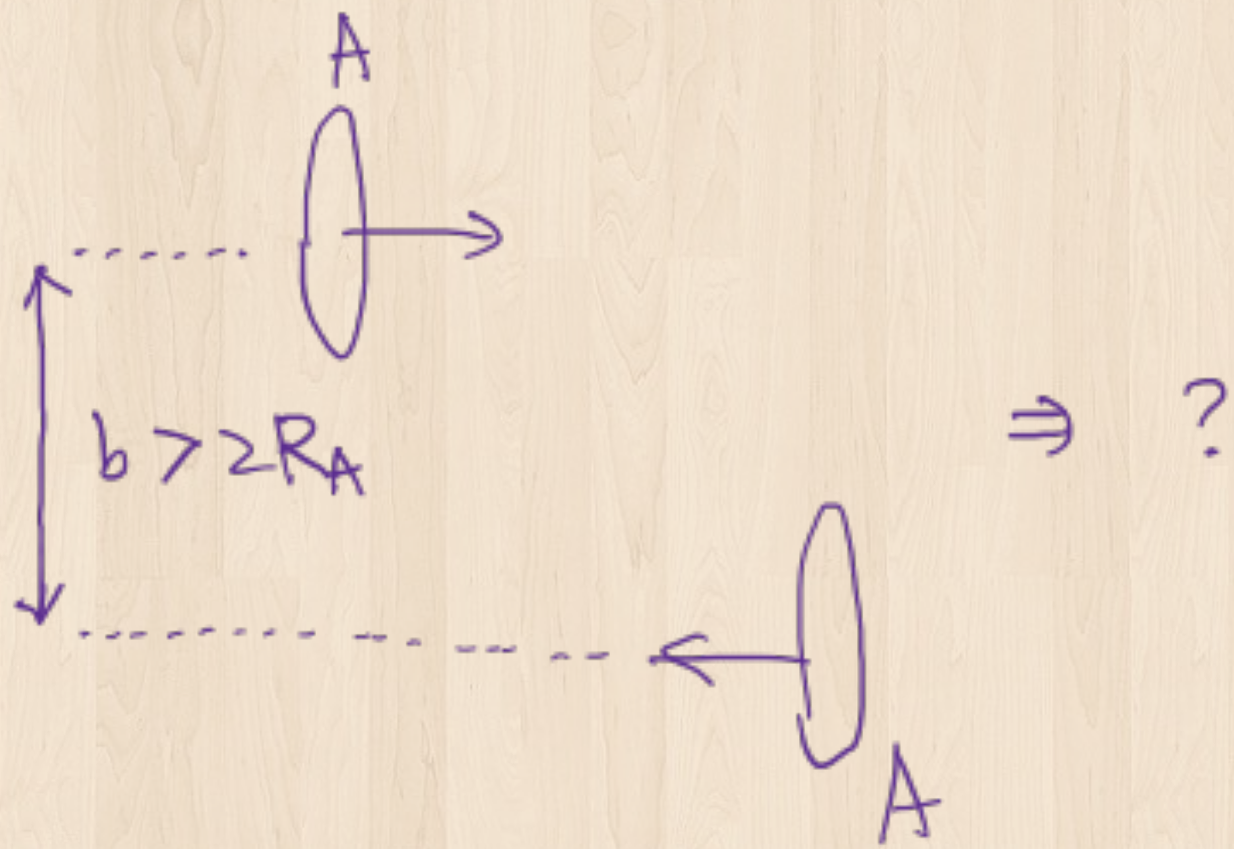
“Scattering” recap

- QGP lifetime is small → no time for electroweak interactions to cause significant effect for high energy photons and electrons/muons
- Heavy quarks are created at the beginning of the collision and samples through the whole QGP evolution
- What we covered are just examples: a lot more we can learn from “scattering experiment” with different particles (not discussed due to time)

What happens when the ions miss each other

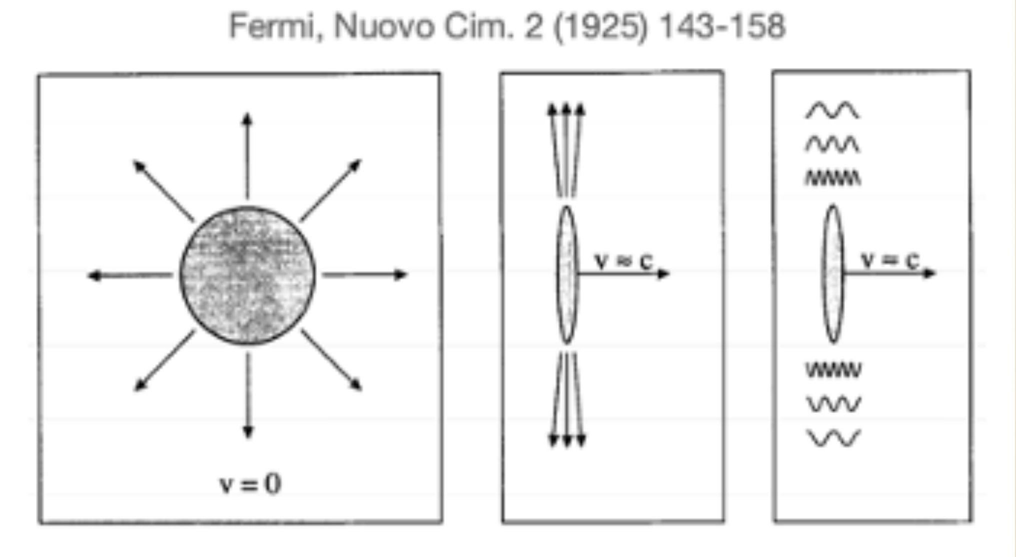
Ultraperipheral collisions (UPC)

- Impact parameter larger than the radius of the two nuclei → ultra-peripheral collision
- No inelastic hadronic interaction but EM interaction possible



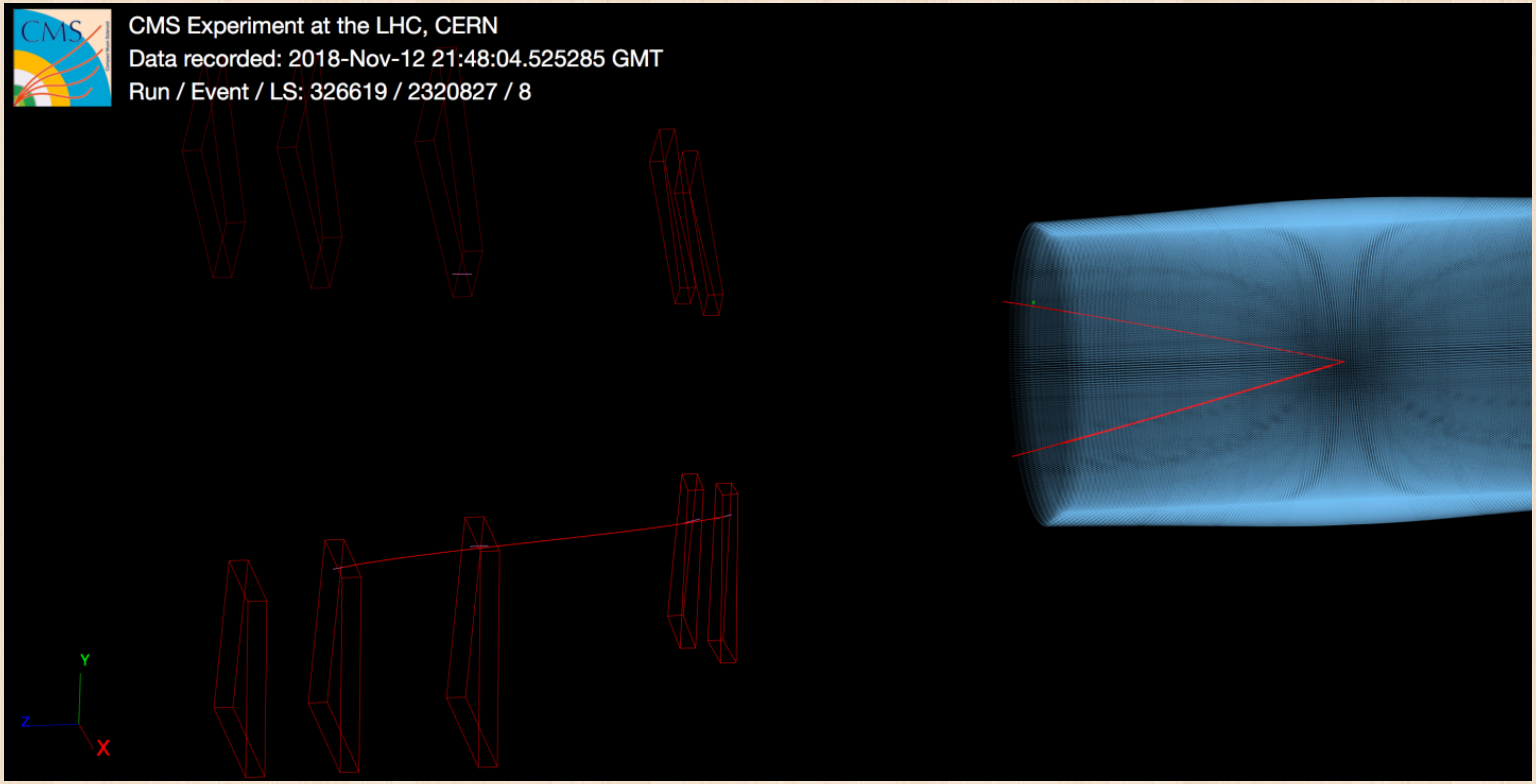
Electromagnetic field as photons

- Lorentz boost à virtual photons around the nucleus
- Photon flux $\propto Z^2 \rightarrow$ huge cross section boost for EM interaction
    - Precision test of QED
- Photon energy $\sim \gamma \hbar c / r$
    - r: distance to nucleus center
    - When it's just outside the boundary: ~80 GeV at LHC



These EM fields can interact with the other ion

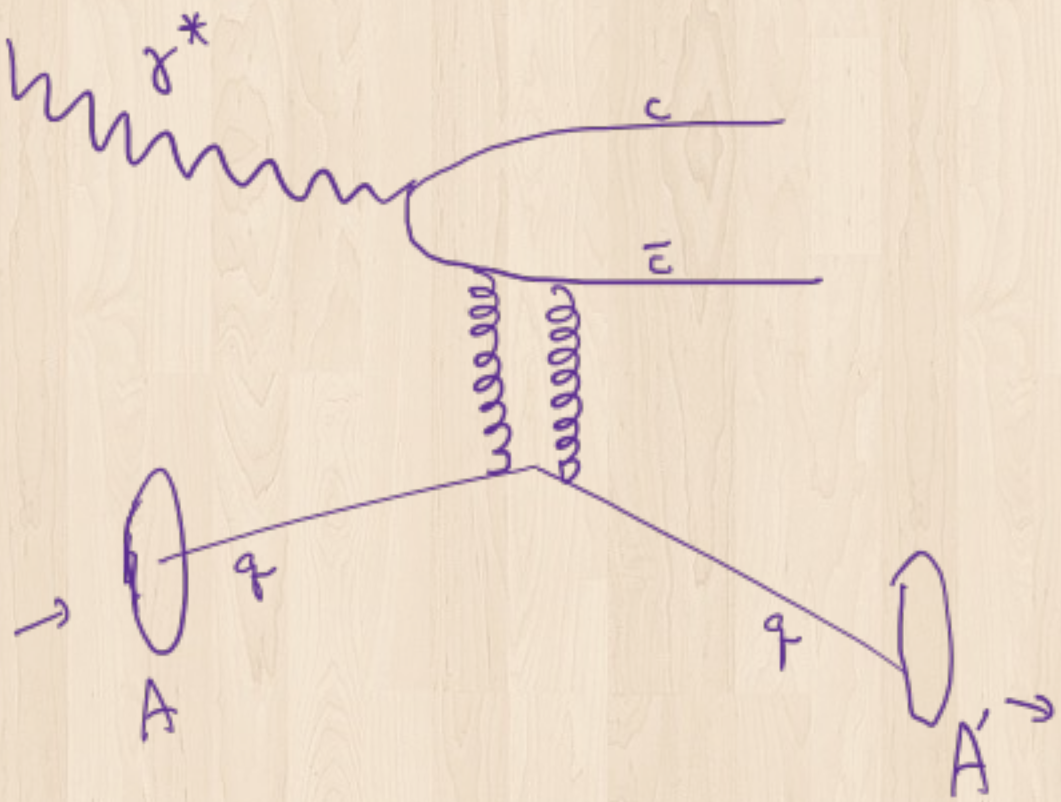
Example: J/Psi production

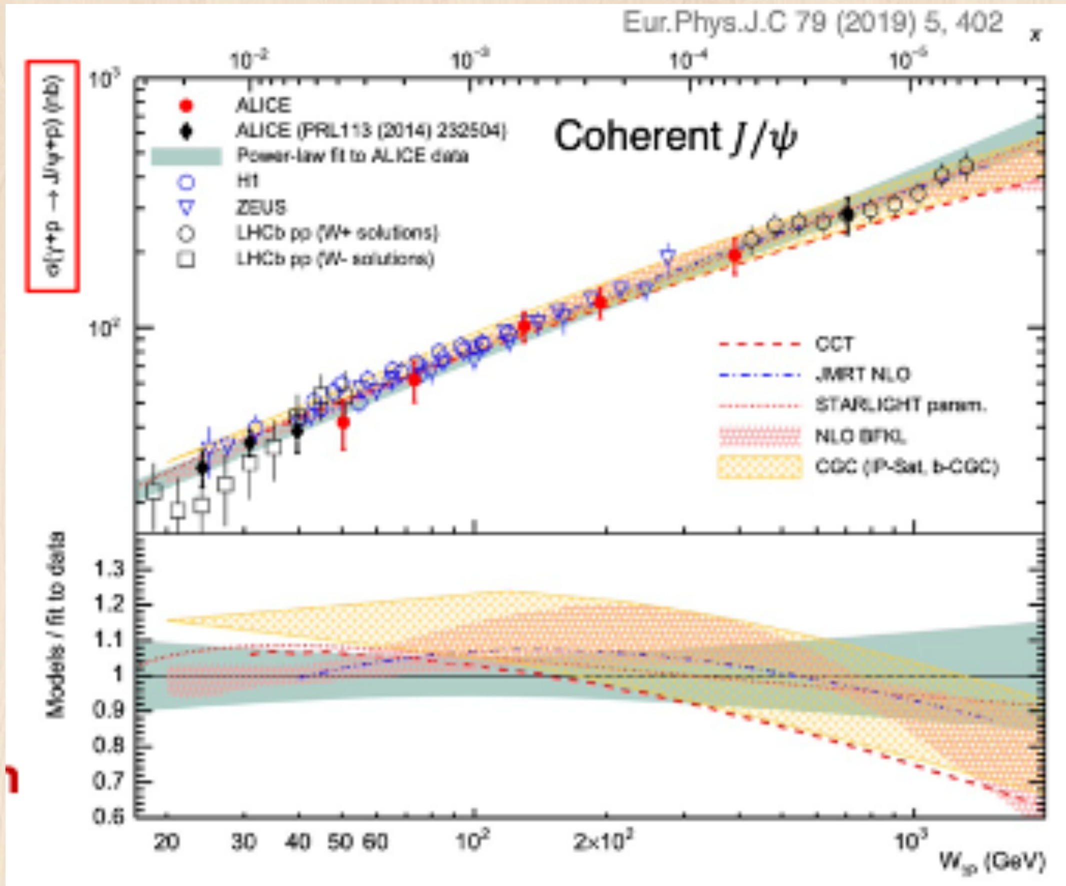


A candidate event with exclusive two muons

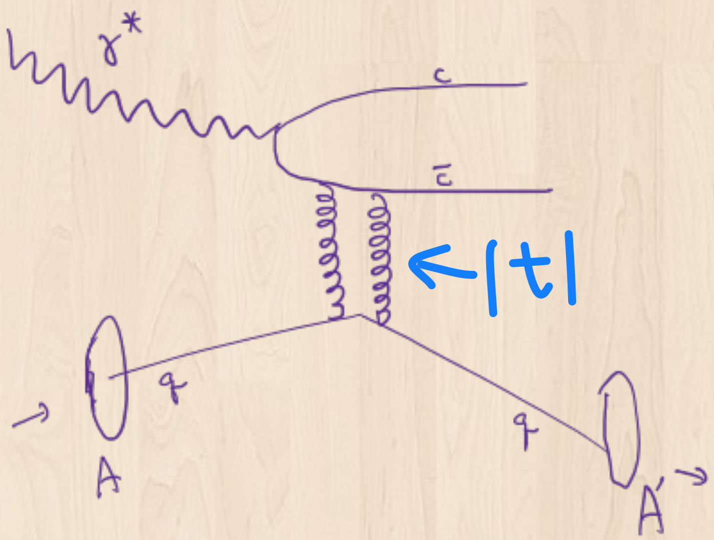
Example: J/Psi production

Coherent: target does not break up
typically smaller momentum transfer
sensitive to gluon PDF

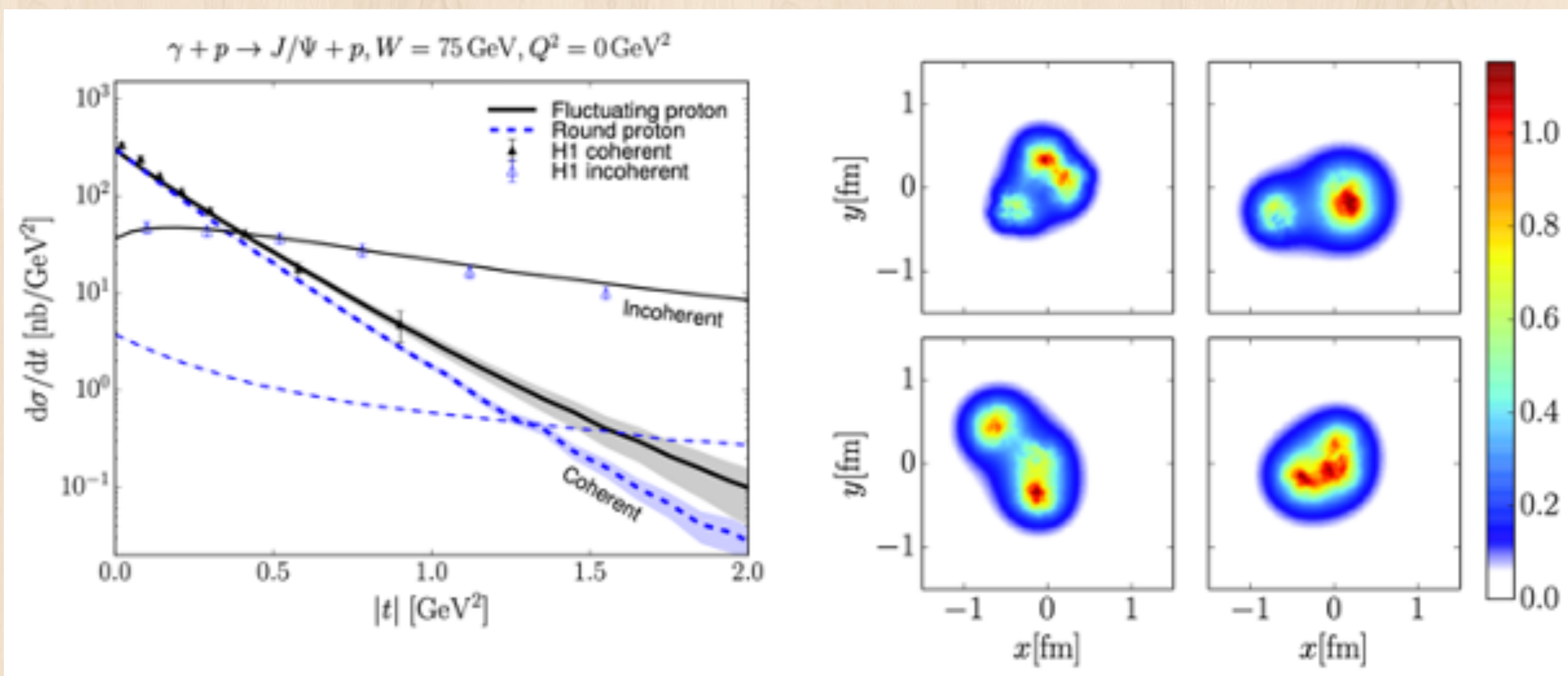




n.b. J/Psi production



Incoherent: typically larger momentum transfer sensitive to sub-nucleon fluctuations

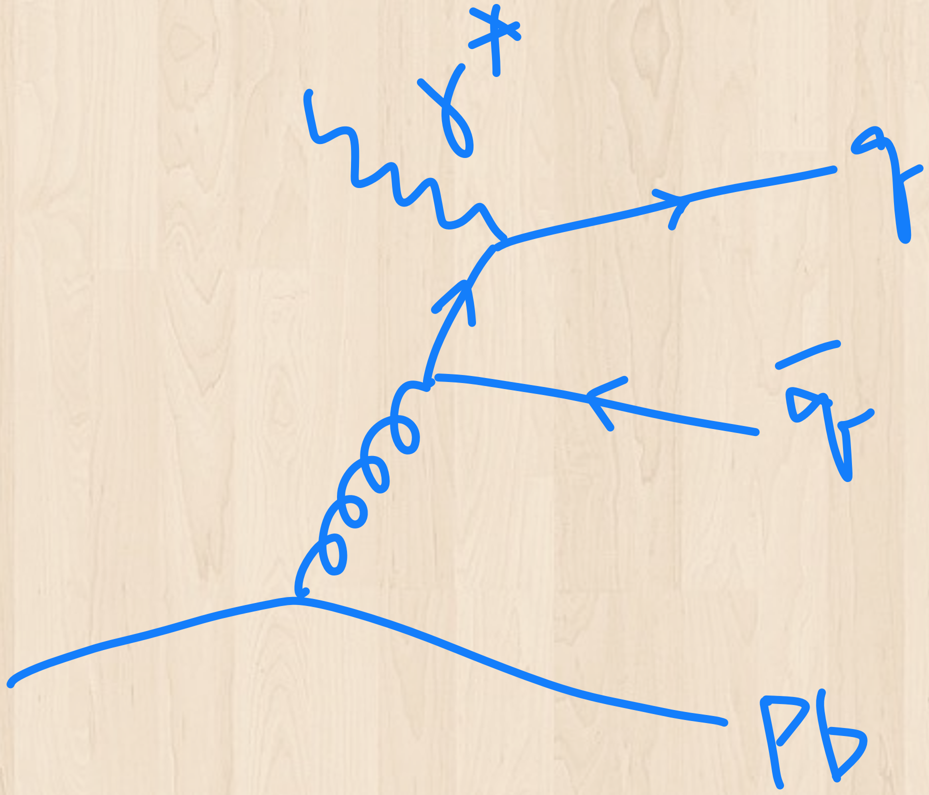


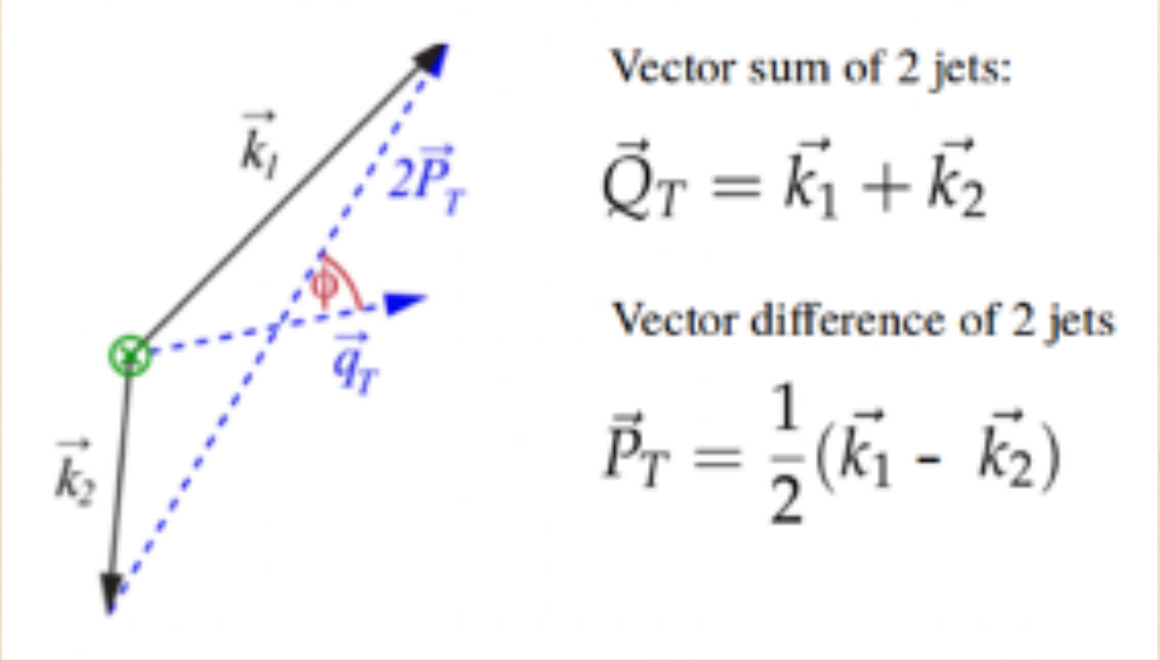
PLB568:205,2003 EPJC46:585,2006

Phys. Rev. D 94, 034042 (2016)

Exclusive dijet

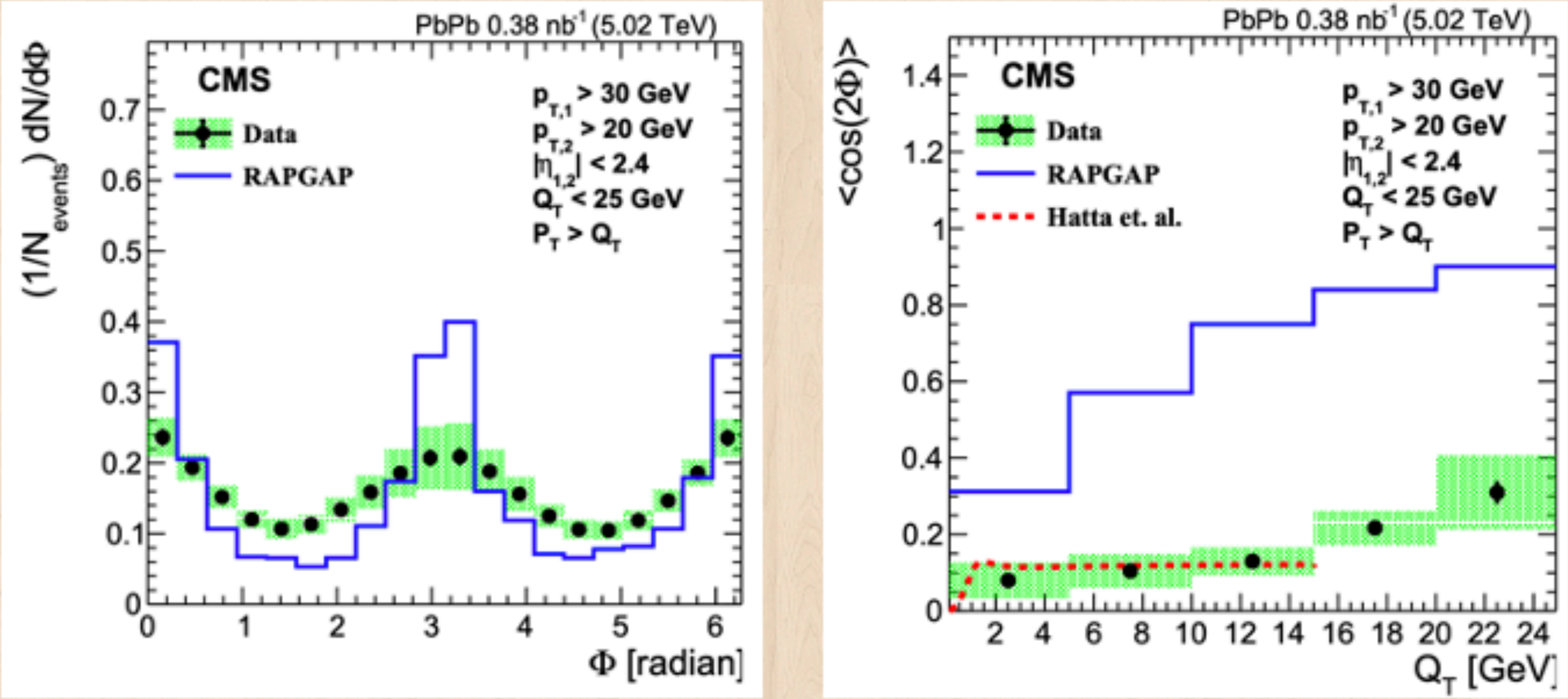
- Ultraperipheral AA collision producing a pair of jets
- $\overrightarrow{P}_T$ = scale; $\overrightarrow{Q}_T$ = “transverse kick” of the dijet system





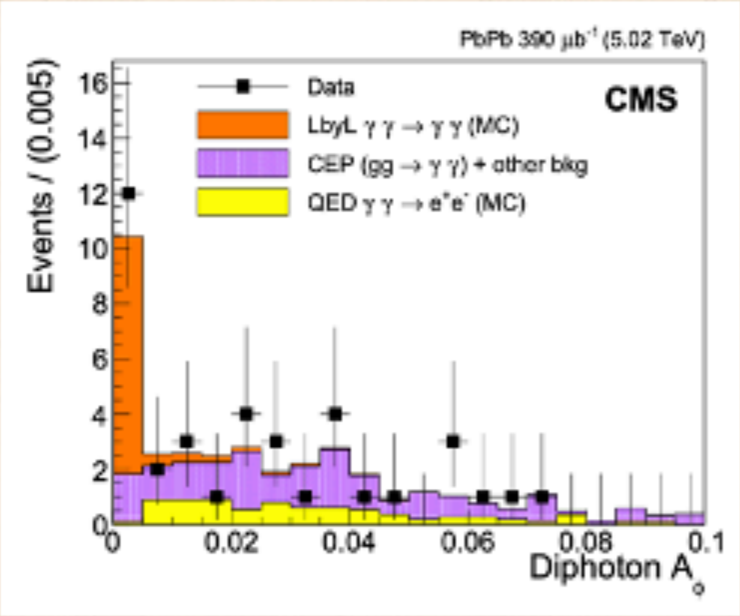
Exclusive dijet

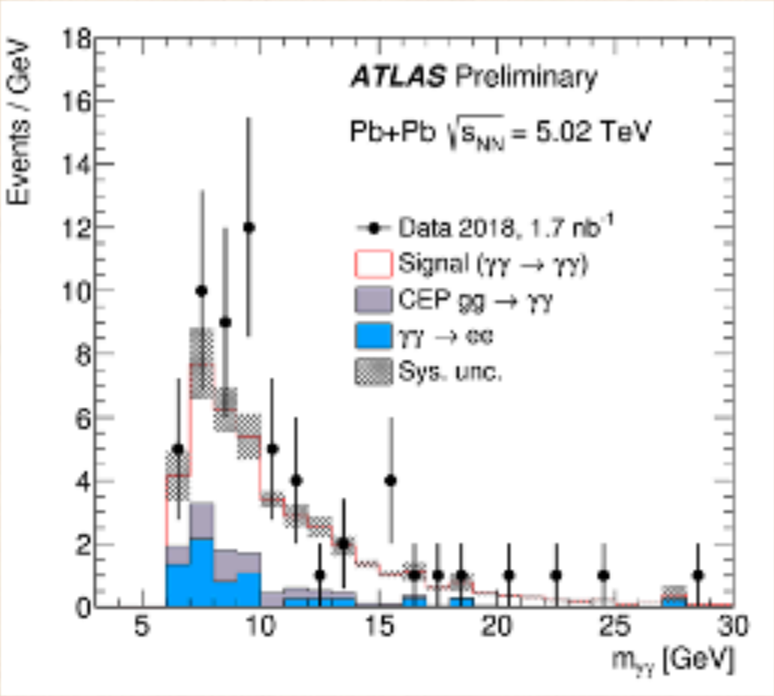
- We do see some modulation, not produced by MC
  - Potential complication: FSR

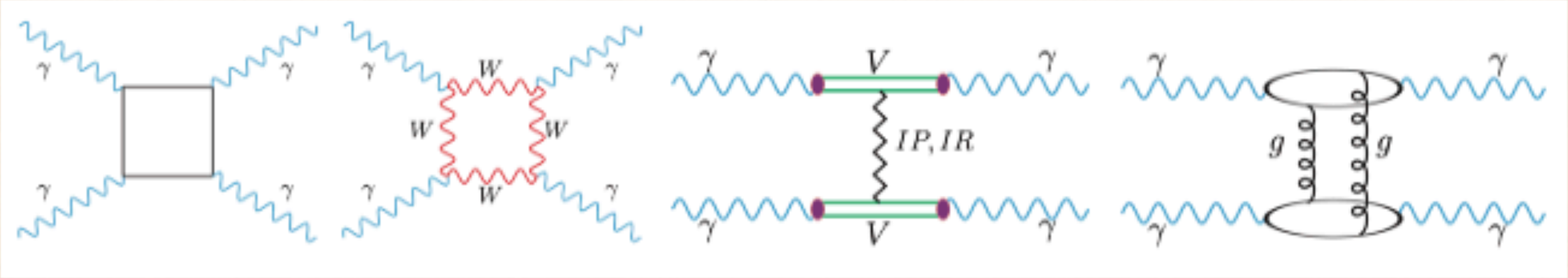


Photon-photon scattering

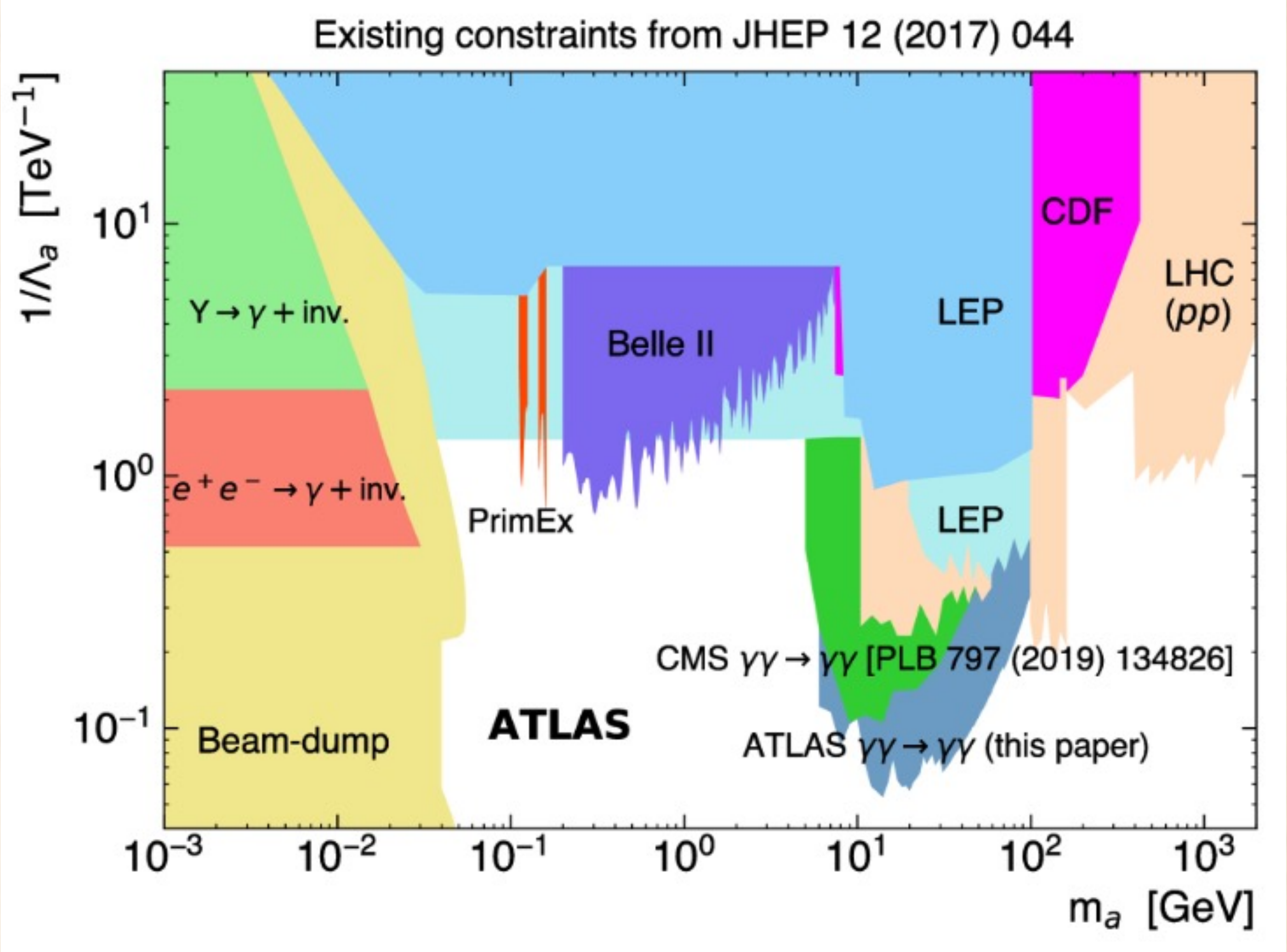
- Photons interact with each other through higher-order diagrams
- Or new physics

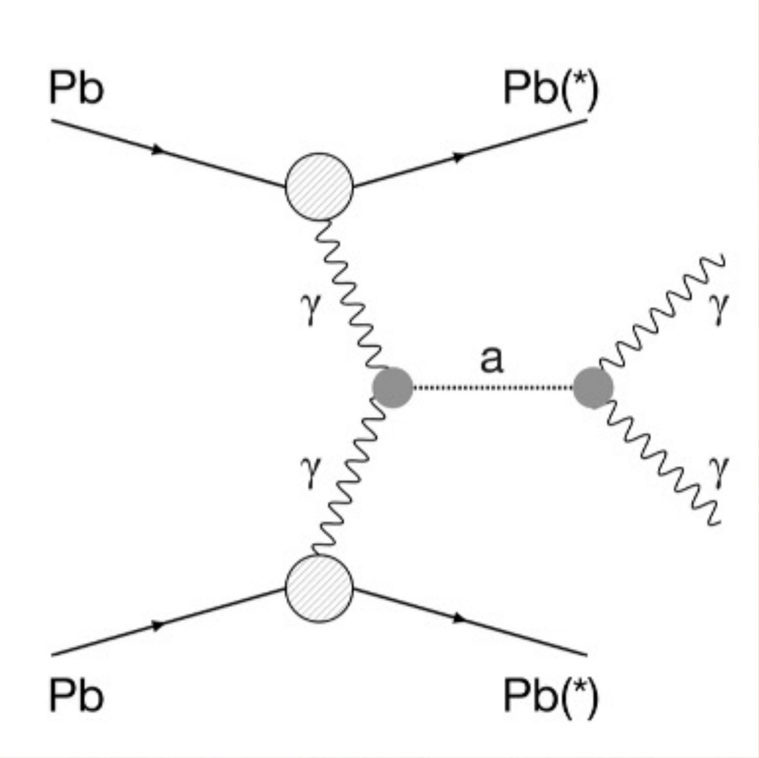






Limits on potential axion-like particle





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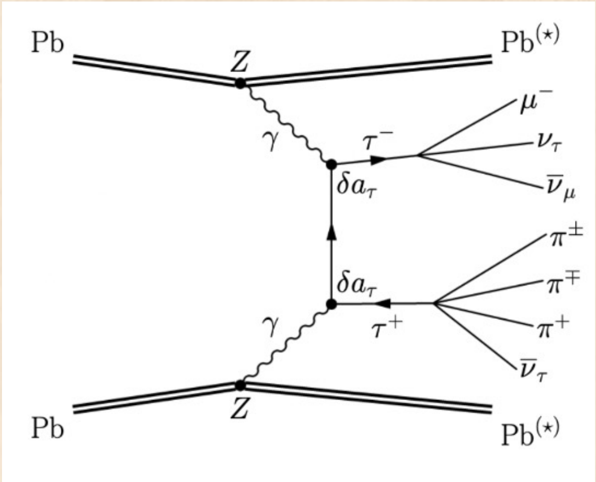
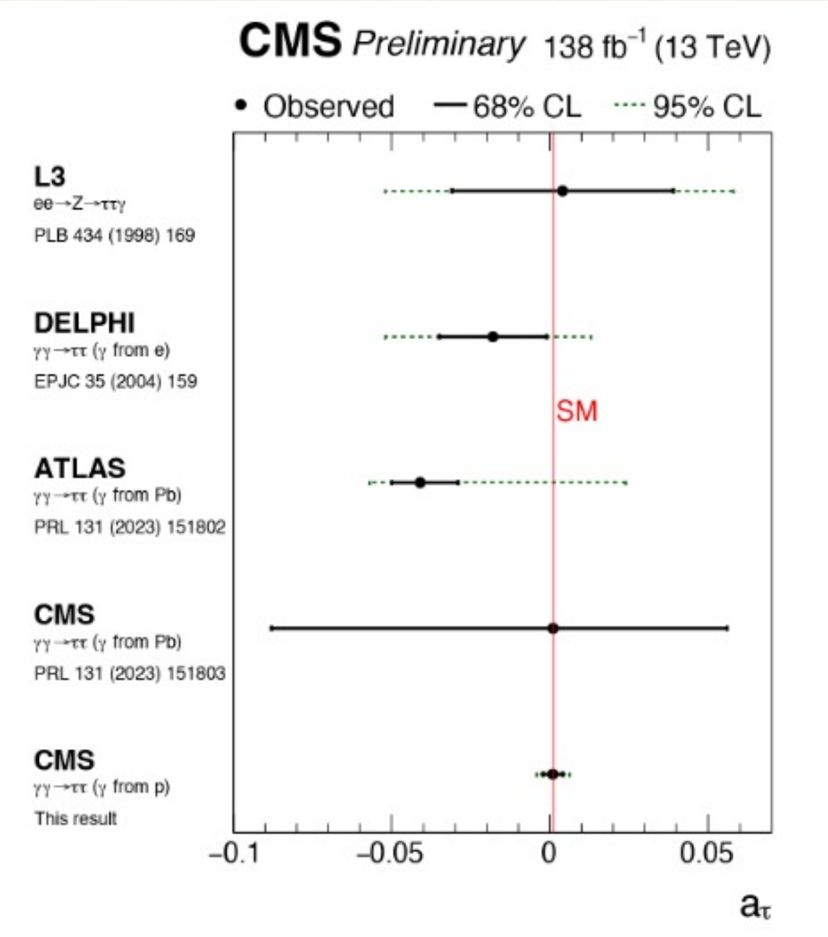
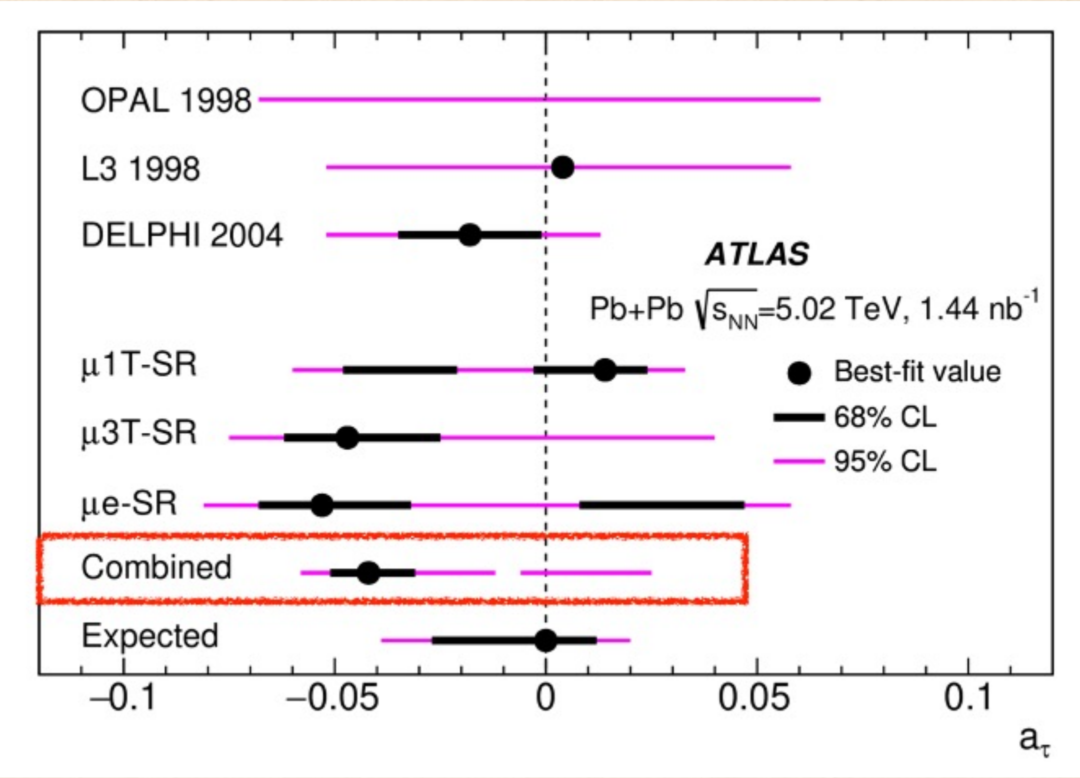
$g_\tau - 2$ with $\gamma\gamma \to \tau\tau$

UPC results competitive with LEP
Looking forward to new data :)







Wrap up: Heavy ions

Synergy with EIC

- Heavy ion results are usually a combination between **hot nuclear effect** (those related to the presence of QGP) and **cold nuclear effect** (PDFs, nuclear energy loss, etc)
  - But not always: in some cases like the UPCs **cold nuclear effect** dominate
- EIC can provide precision measurements on many things on the **cold nuclear effect** side

Heavy ion collisions

- Due to time constraints a lot of interesting subfields are not mentioned — happy to discuss more later :)
- QGP: phase of matter where partons are not confined in hadrons
  - Behaves like a hot quantum liquid
  - We can study it through the decay products or through interaction of particles with it
- Ultraperipheral collision (UPC): ions miss each other and we have EM-initiated interactions
- Synergy and connection with other fields of study, including EIC physics

Part 2: Jets

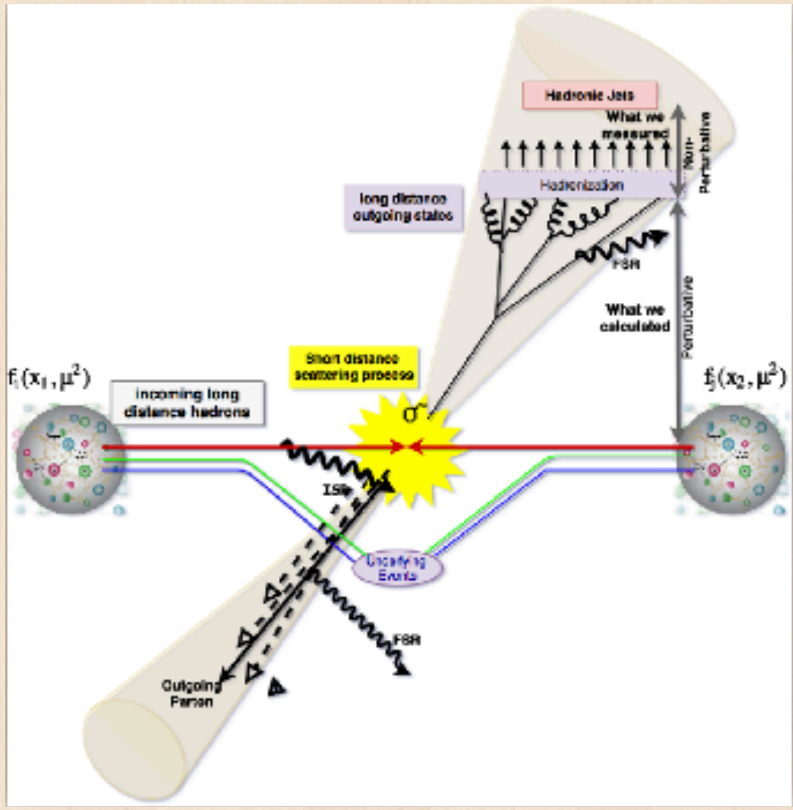
Goals for this part

- **Heavy ion physics**: what is it, why do we study it, how is it relevant to EIC
- **How do we study the QGP?** What have we learned?
- **Jets basics**: what are they and how do they develop in vacuum? What do they look like?
- **Application of jets**: Why do we love them & how do we use it in various contexts to learn the physics we are after?

Jets in vacuum

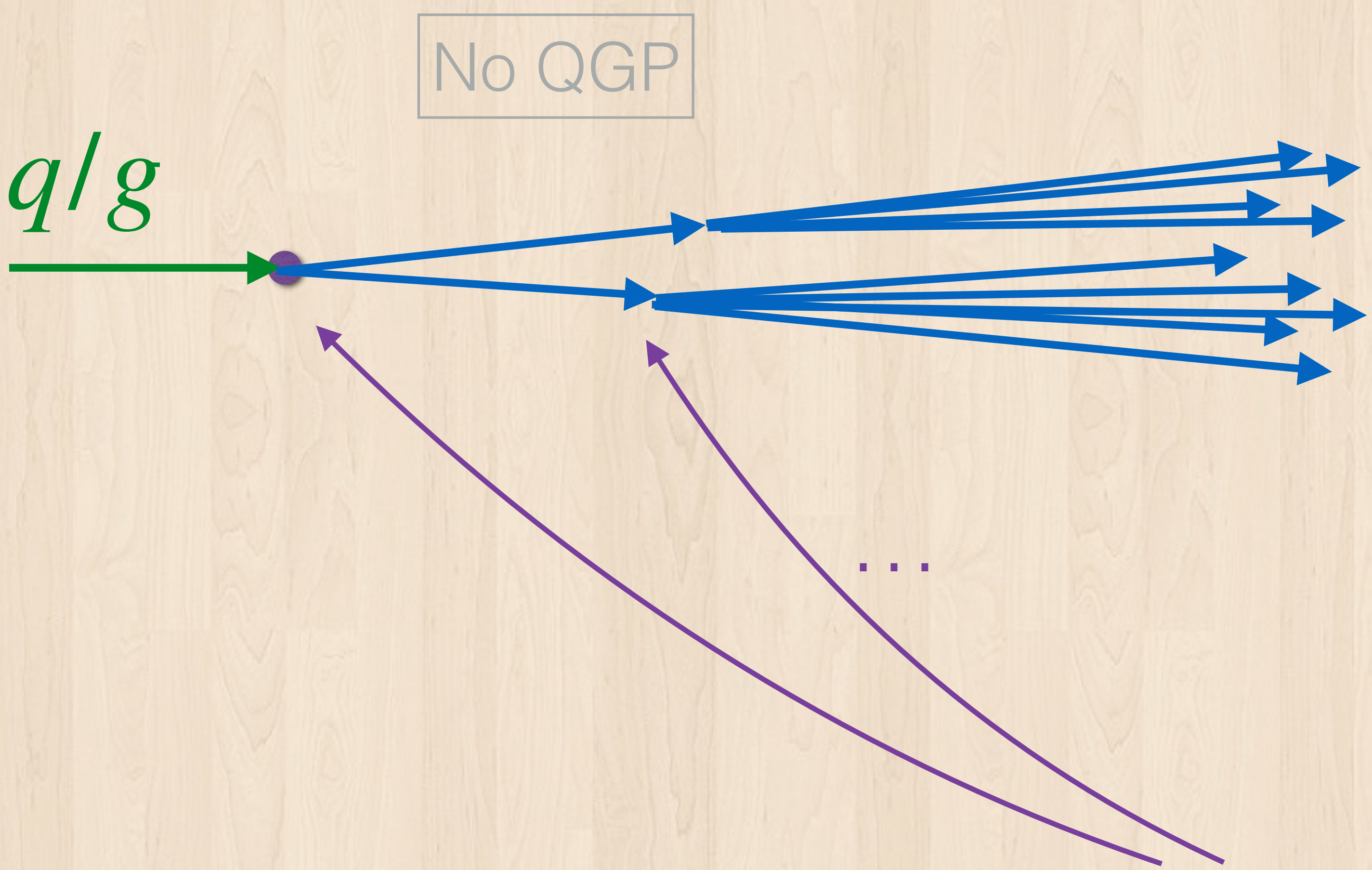
Partons from collisions

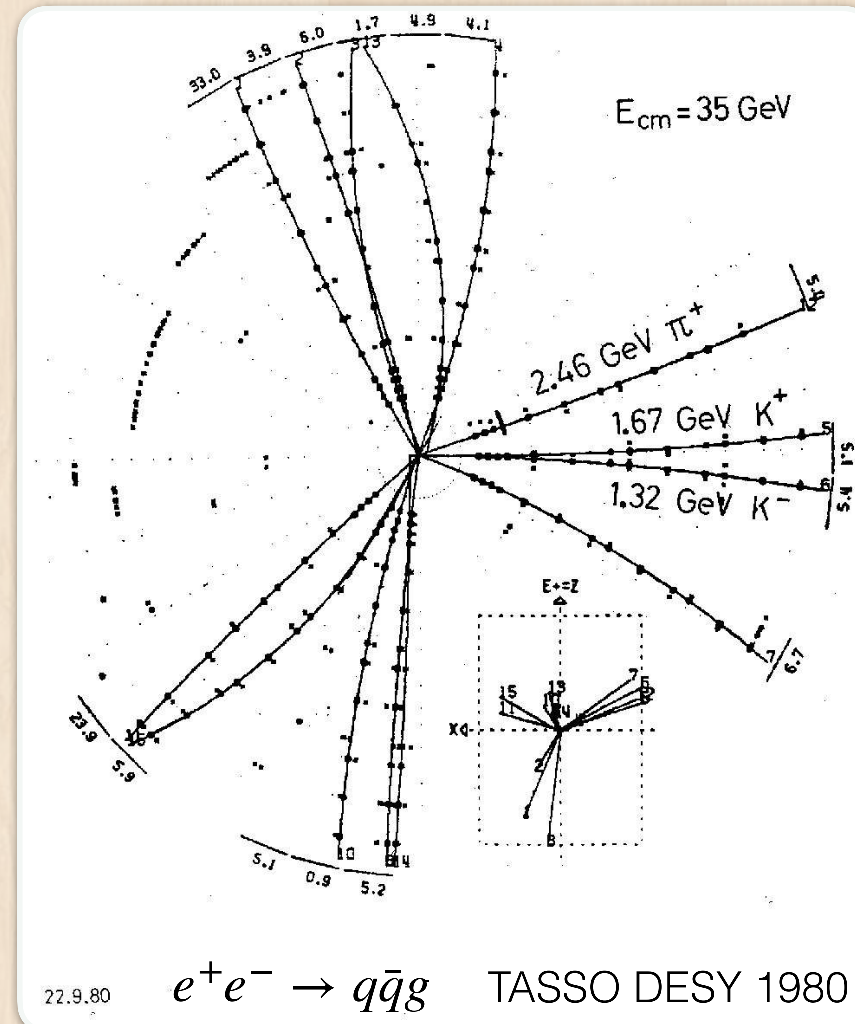
- Suppose we have high-energy quarks or gluons going out in collision



- It carries high virtuality Q^2
    - "Violentness" of the collision
    - Highly virtual = "imbalanced" momentum: $E^2 - p^2 \neq m_0^2$
    - Link to uncertainty principle

q/g shower into jets



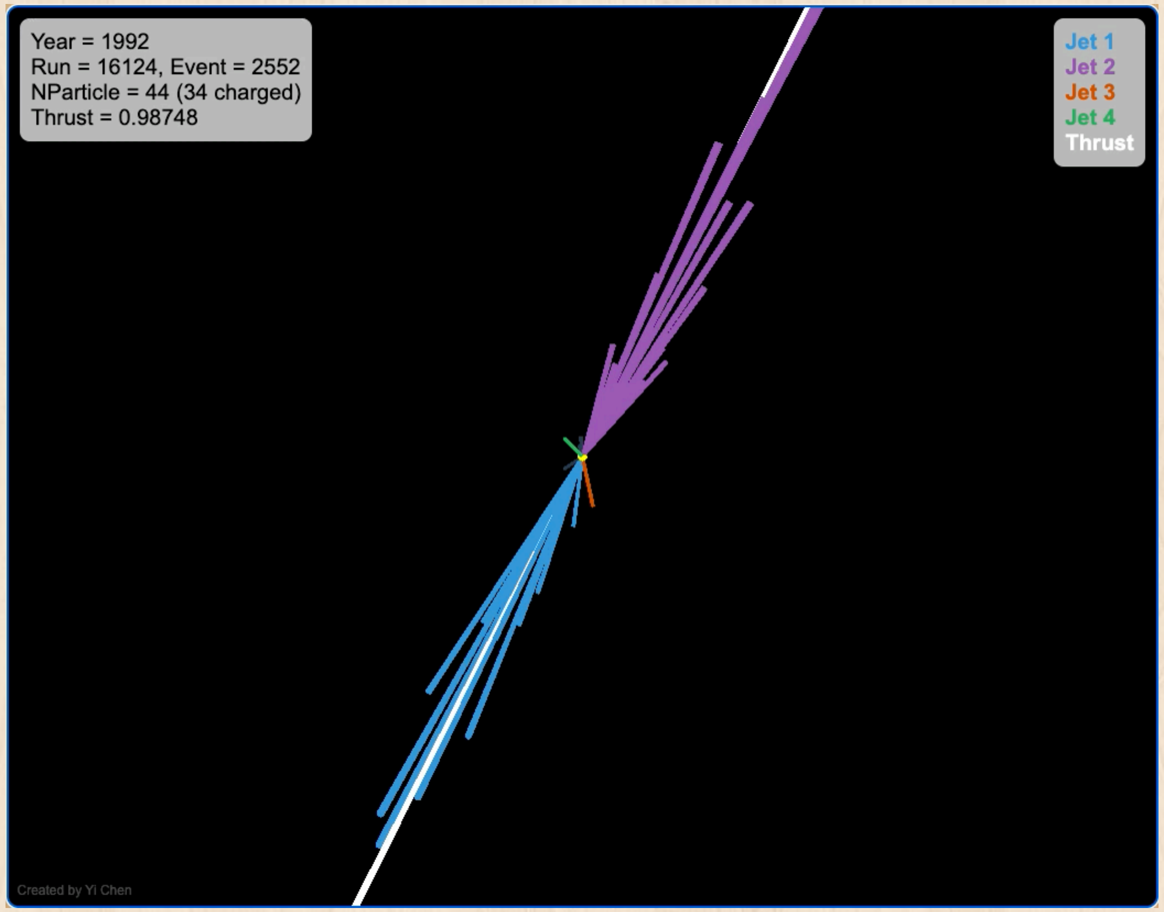


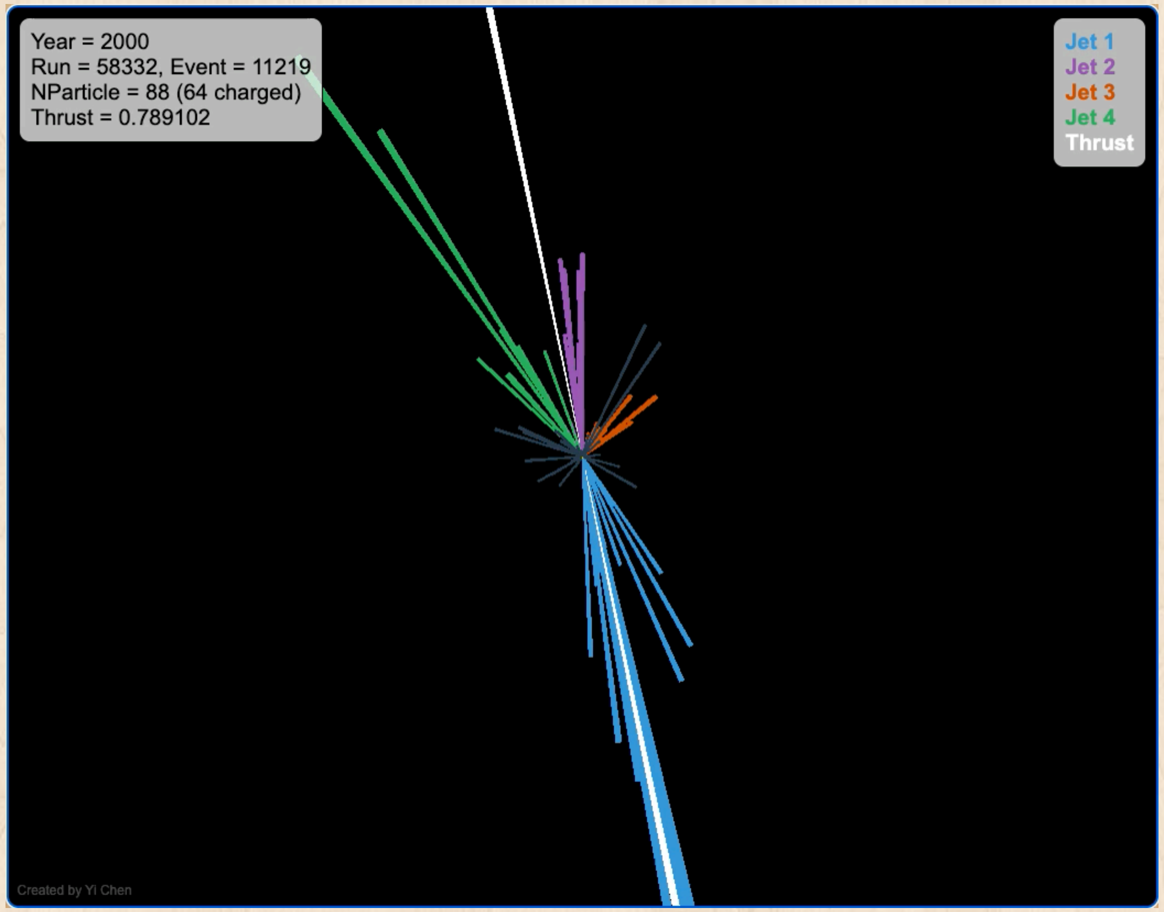
Highly virtual g/q **split** repeatedly

Each g/q develops into a spray of final particles (= jets)

Jets = proxy for initial g/q

Examples of how it looks like

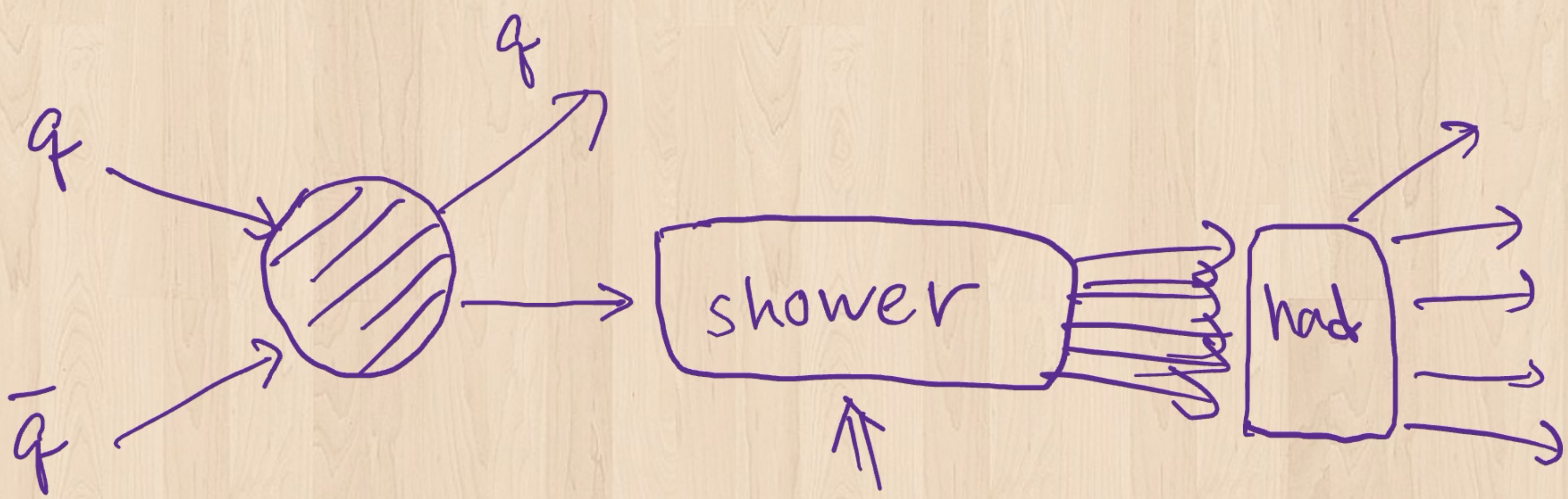




Examples from e^+e^- collision from ALEPH

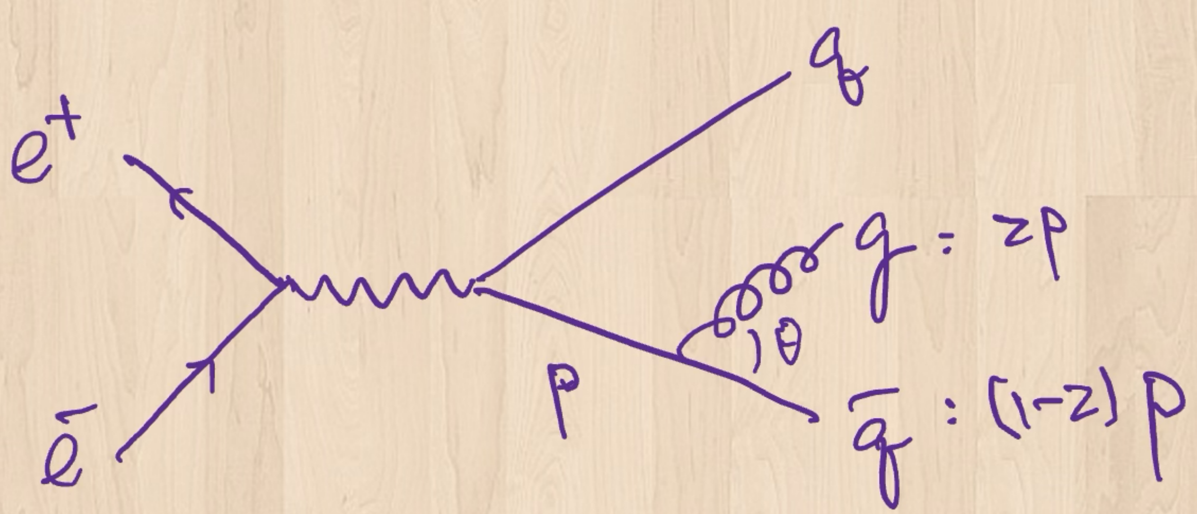
Parton shower: closer look

- Parton shower refers to the process where a parton (quark and gluon) develops into a spray of roughly collinear partons
- Key ingredient in modeling inelastic hadronic collisions



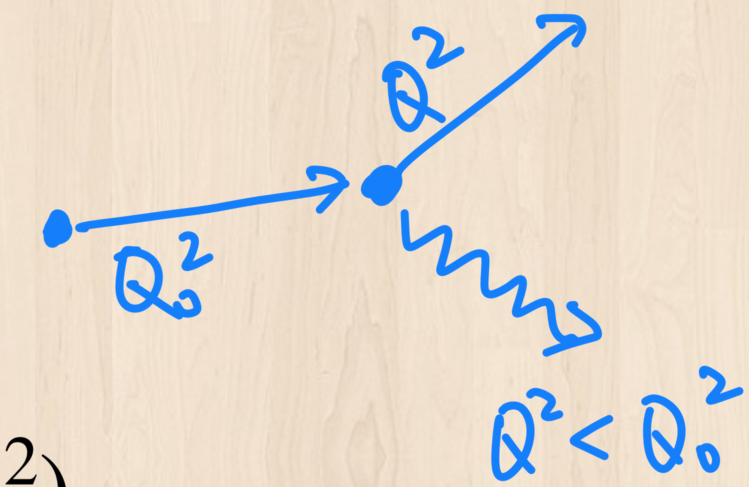
Parton emission example

- Example: $e^+e^- \to q\bar{q}g$
  - $\frac{d\sigma_{q\bar{q}g}}{d\cos\theta\, dz} \simeq \sigma_{q\bar{q}} C_F \frac{\alpha_s}{2\pi} \frac{2}{\sin^2\theta} \frac{1+(1-z)^2}{z}$
  - θ = angle between quark and gluon
  - z = energy fraction of gluon
- Both collinear and soft divergent
  - Consequence: things are more likely at small θ and z



Simulating the shower: roadmap

- Strategy: build emission probabilities using cross sections
- Pick an ordering variable to evolve things
  - Example: virtuality Q^2



- Build "first-emission probability" $P(Q^2; Q_0^2)$
  - Emission at Q^2 (from cross-sections)
  - No emission between scales Q_0^2 and Q^2 ("Sudakov form factor")
- Throw dices repeatedly until hadronization scale

Choice of “ordering variable”

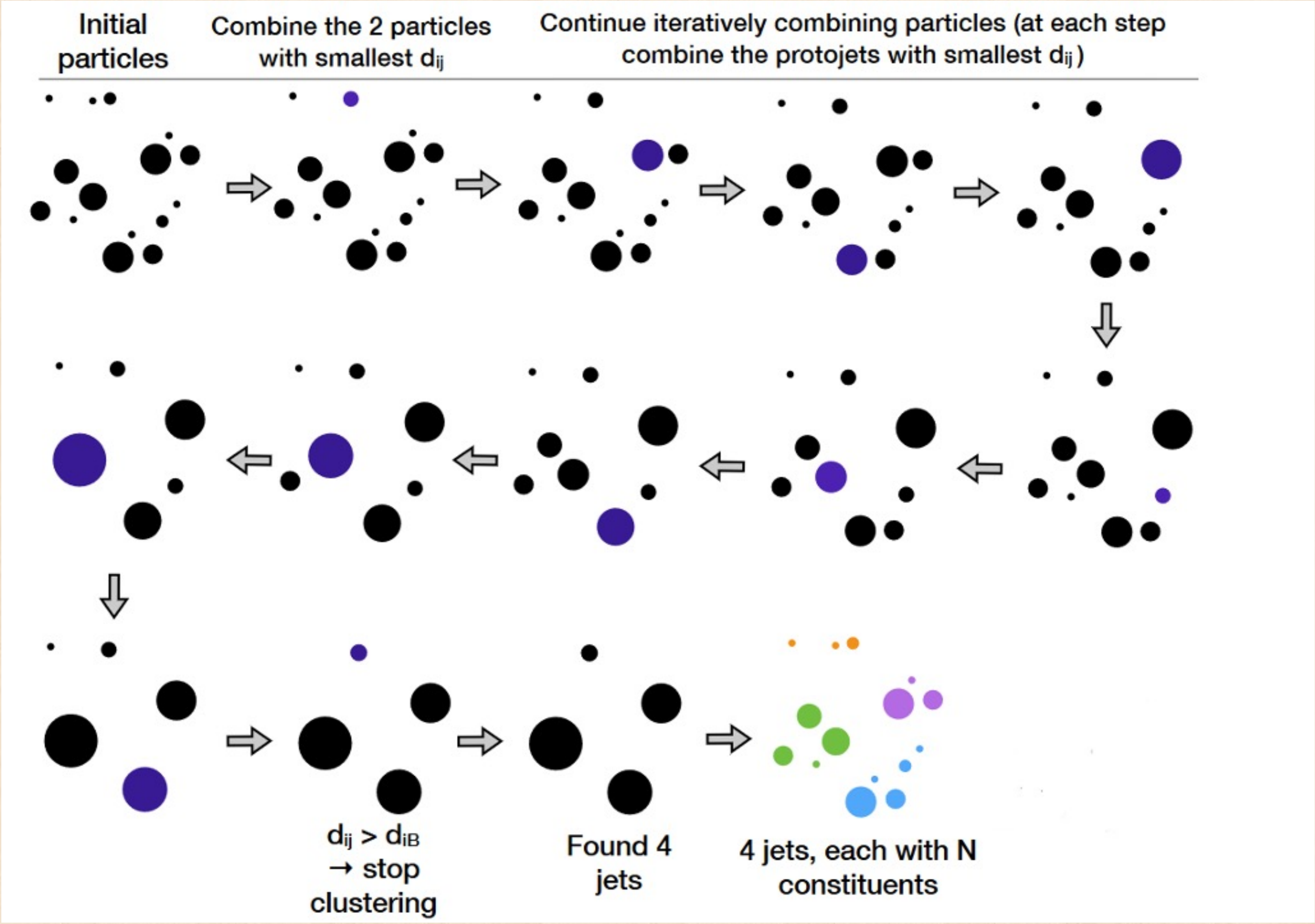
- Some examples
  - Angle
    - Large angle splitting goes “first”
    - Then we systematically go to smaller and smaller angle
  - Virtuality
    - Shower starts from the largest virtuality splitting
  - Transverse momentum (transverse to parton)
  - …
- Bottom line: these are **choices**. And they give different “shower history”
  - In vacuum, all that matters is that the final particle distribution is ok (very different story in QGP)

How do we find jets in experiments?

How do we find them?

- We don't know what comes from what → "**clustering algorithm**"
- Example: sequential recombination algorithm
  - Pick some measure to evaluate distances
  - Find the two closest and merge them
  - Repeat until done
- Stopping condition
  - **Inclusive**: stop when the minimal distance is large enough
  - **Exclusive**: if we have only N particles, stop

Sequential recombination



The k_T family of algorithms

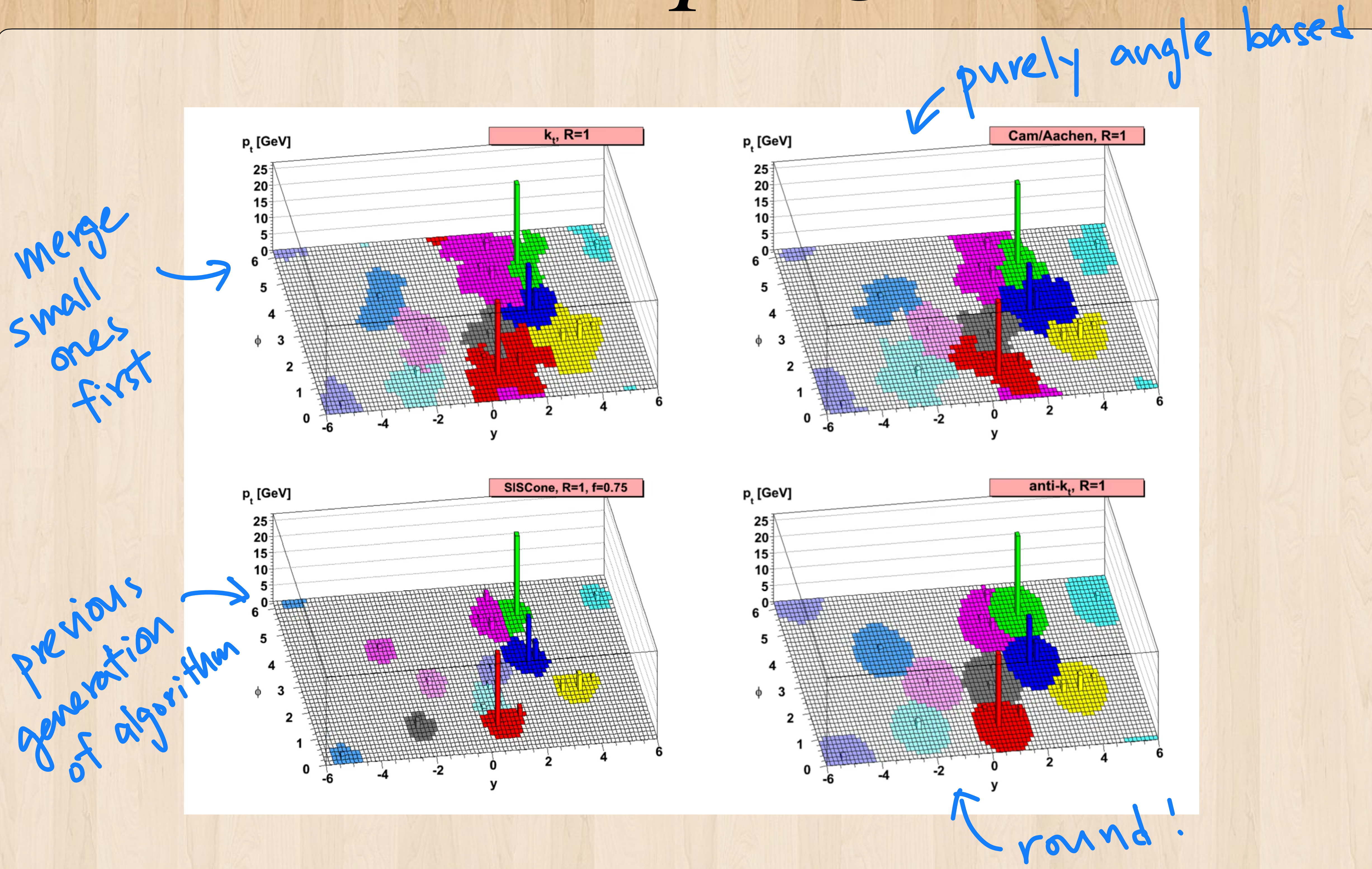
- Distance $d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right) \times \frac{\Delta y^2 + \Delta\phi^2}{R_0^2}$

  angles

  weighted by p_T factors

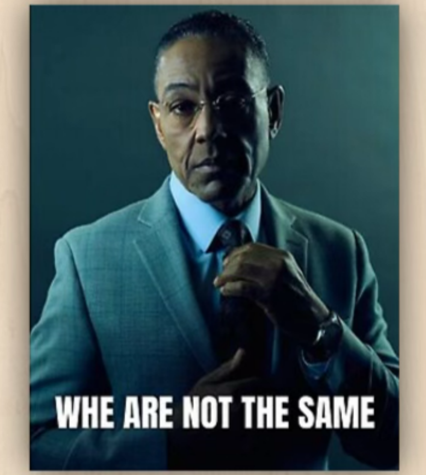
- Stopping condition $d_{iB} = p_{T,i}^{2p}$
- R_0: “resolution parameter” → roughly size of jet
- Some special choices of p
  - $p = 1$: k_T clustering — small p_T grouped together first
  - $p = 0$: Cambridge/Aachen clustering — p_T independent
  - $p = -1$: anti-k_T clustering

The anti-k_T algorithm



JHEP 0804:063,2008

Back to the definition of jets



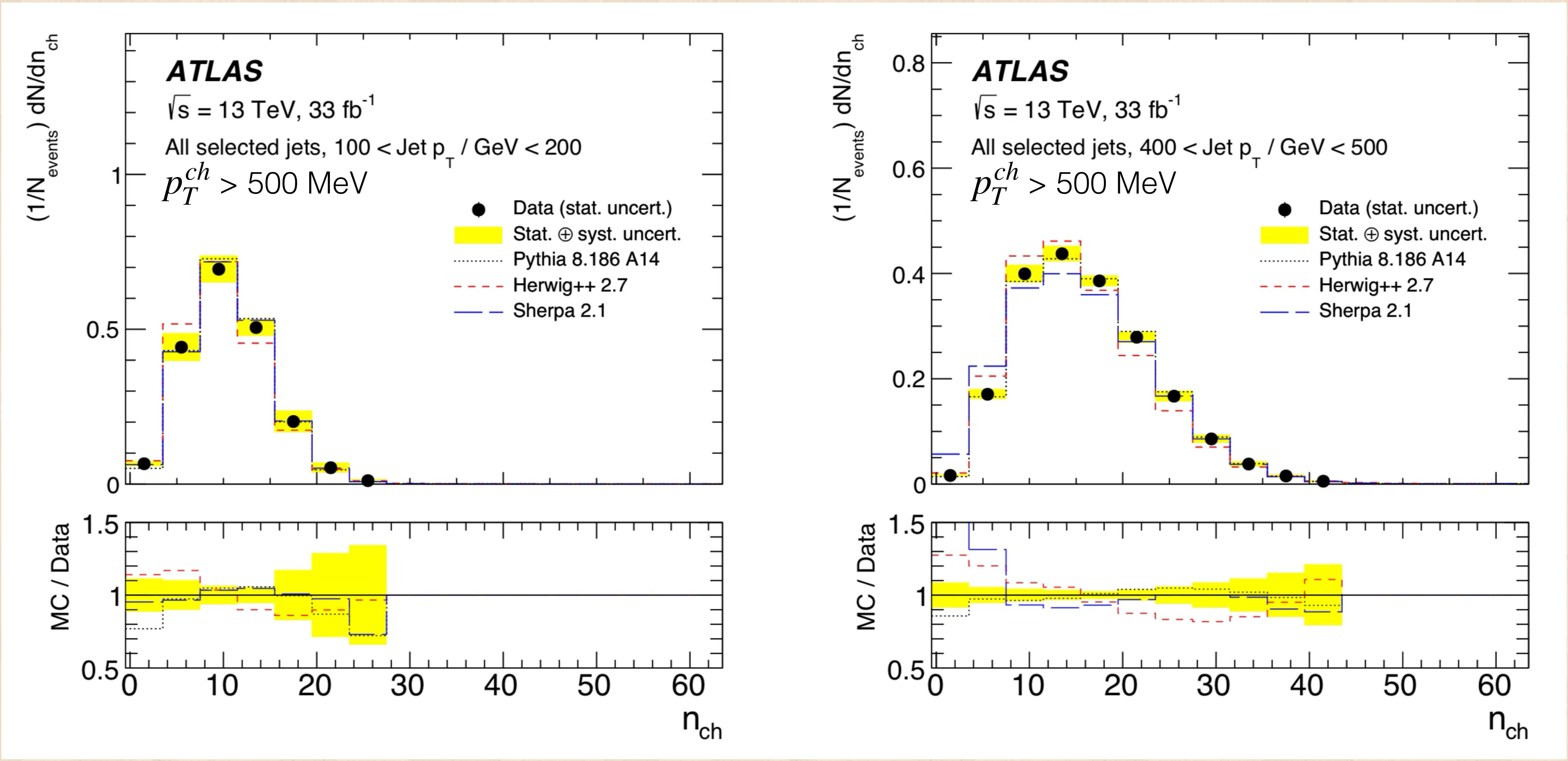
- We have different definitions
  - Conceptually – everything that originates from high-energy quark/gluon
  - Practically – whatever the algorithm gives us
- Consequence: different algorithms give different definitions of jets
  - Connection between what the algorithm gives us and what we like to think conceptually varies
  - Need same algorithm to compare theory and data

Jets in detectors

- Jets are mostly made up of light hadrons
  - Note $\pi^0 \to \gamma\gamma$ so we also get a bunch of photons
- Remember the parton shower splitting function → soft divergence
- We naturally get a lot of soft particles
  - Consequence: we won't see the softest particles. Even if the detector is perfect otherwise, we won't see all the energy contained in a jet
  - Another consequence: (visible) jet energy is different depending on how the shower develops
- **Need corrections to "fill in the missing parts"**

What do jets look like?

Number of particles

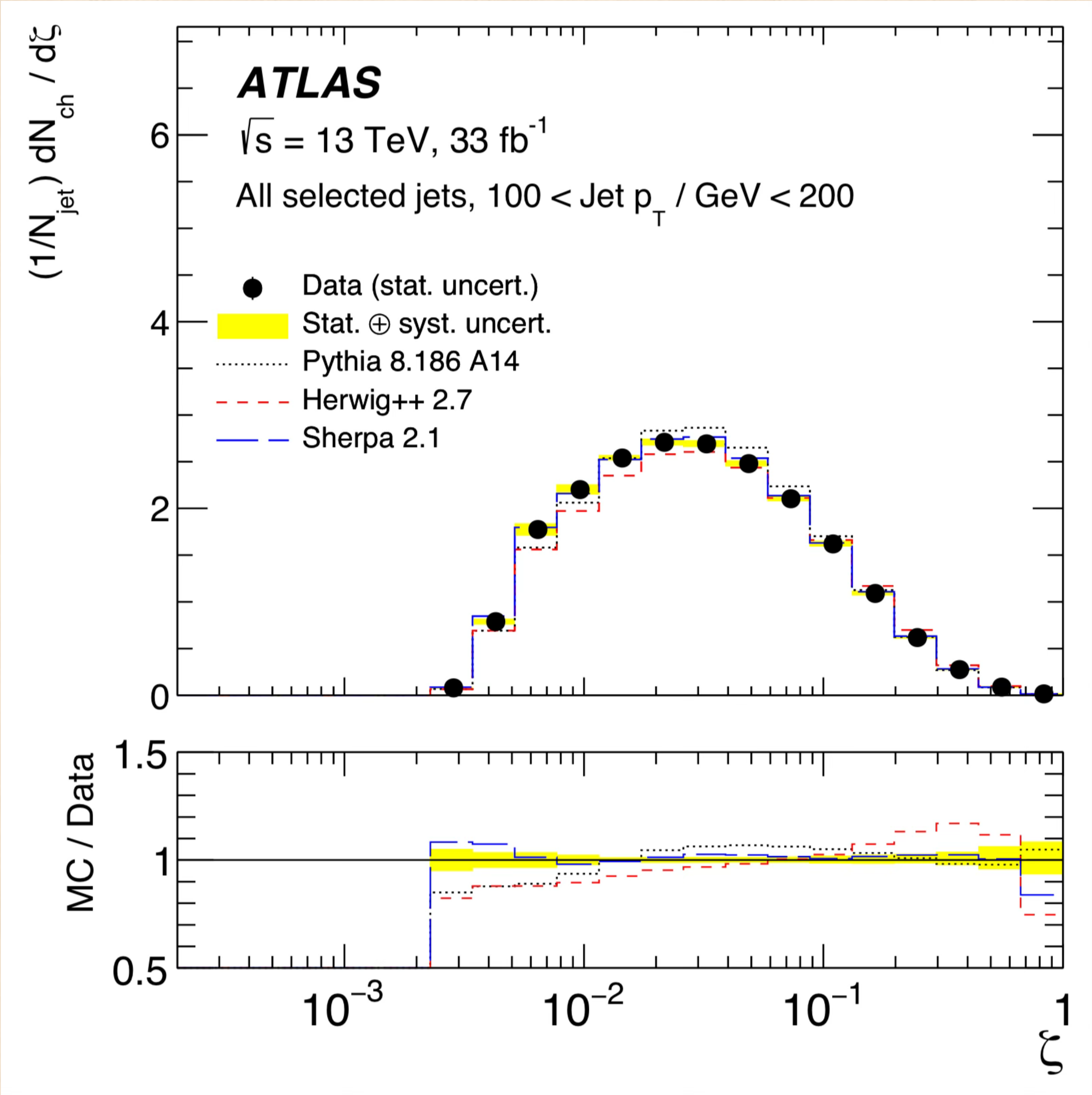


O(10-20), depending on jet energy

Phys. Rev. D 100, 052011 (2019)

Momentum of particles

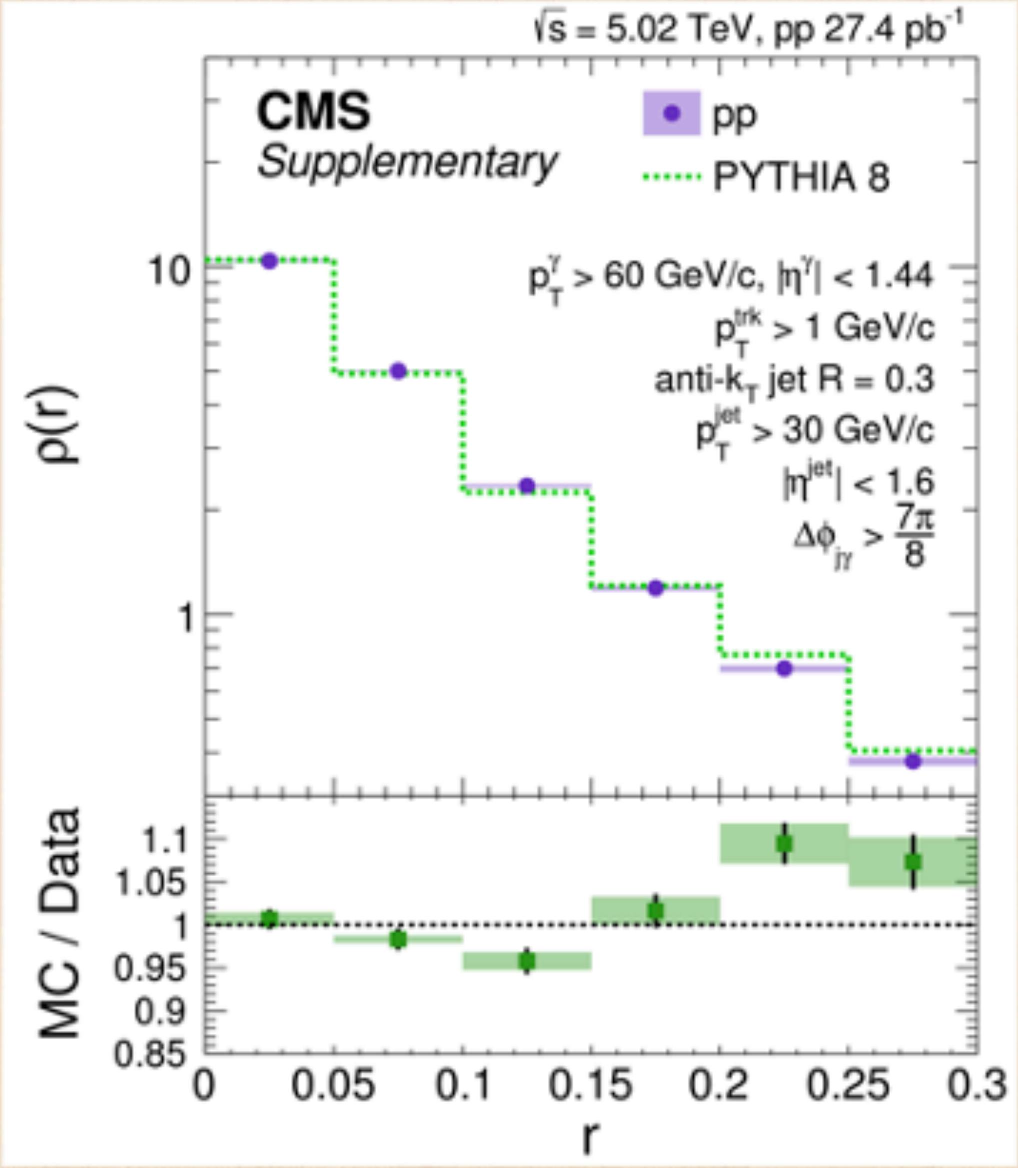
- $\zeta = p_{T,ch}/p_{T,jet}$
- Dominated by lower momentum particles



Phys. Rev. D 100, 052011 (2019)

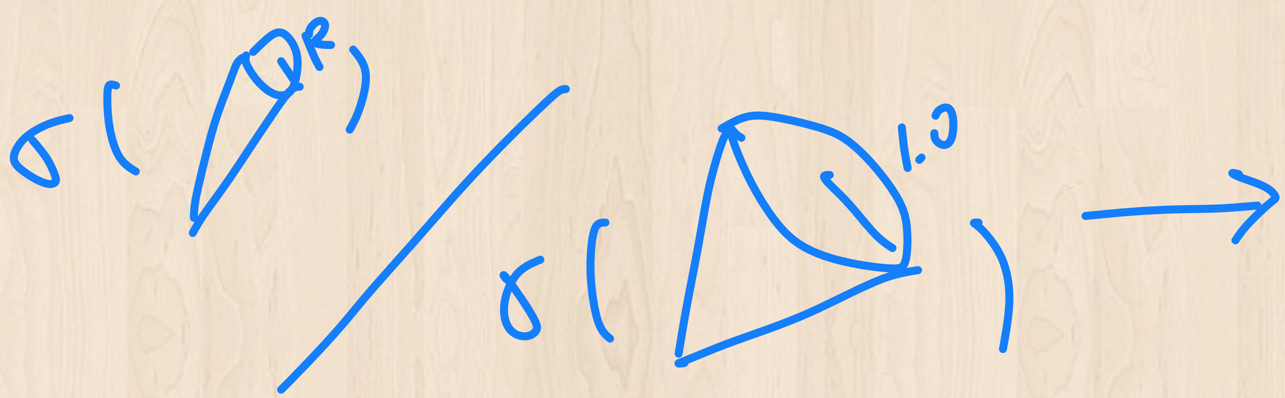
Shape of the jet

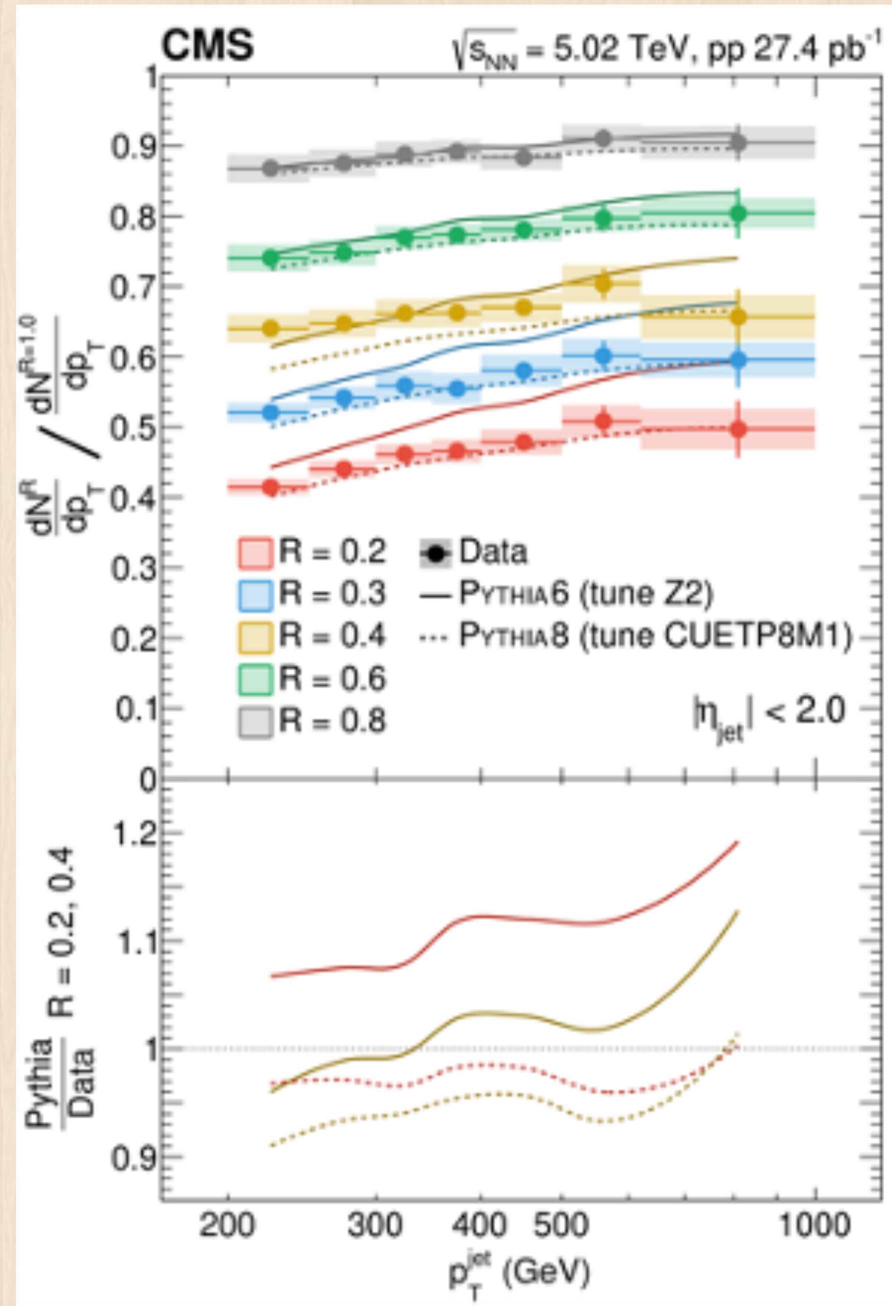
- How much momentum is contained within some distance from center of jet
- $\rho(r) = \frac{1}{\Delta r} \frac{\sum_{jet} \sum_{r_a}^{r_b} (p_T / p_T^{jet})}{\sum_{jet} \sum_{0}^{r_0} (p_T / p_T^{jet})}$
- How much momentum is contained within r < 0.05?



Cross section vs R

- Cross section ratio between different size jets





  - These are anti-kT jets
  - They are mostly round
- 10% extra cross section between R = 1.0 vs R = 0.8

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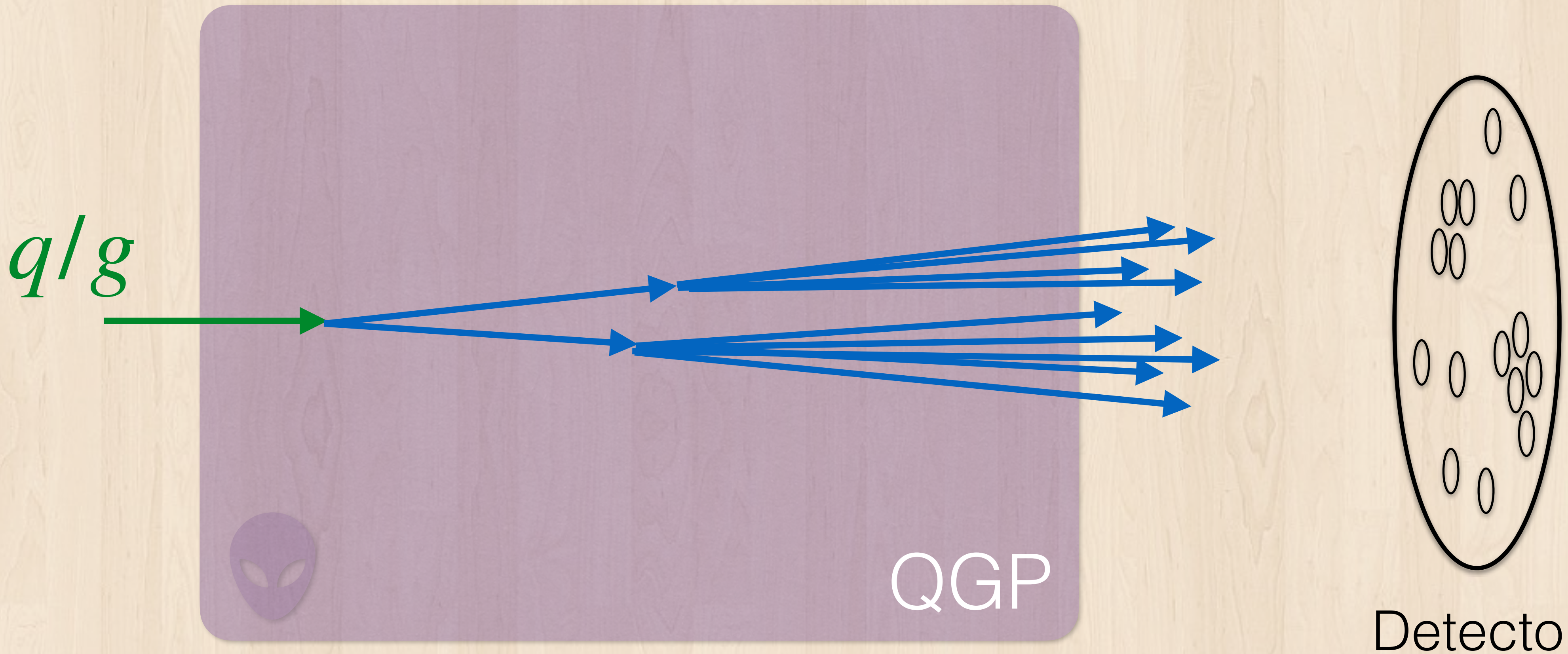
So what do jets look like?

- Concentrated: most of the energy concentrated in small radius
  - But they do extend quite a bit
- Fragmentation: a lot of soft particles
  - Mostly light hadrons (e.g. pions)
- Number of charged particles: typically up to like 10-20 at LHC energies (lower for EIC/RHIC)

Jets in Heavy Ions

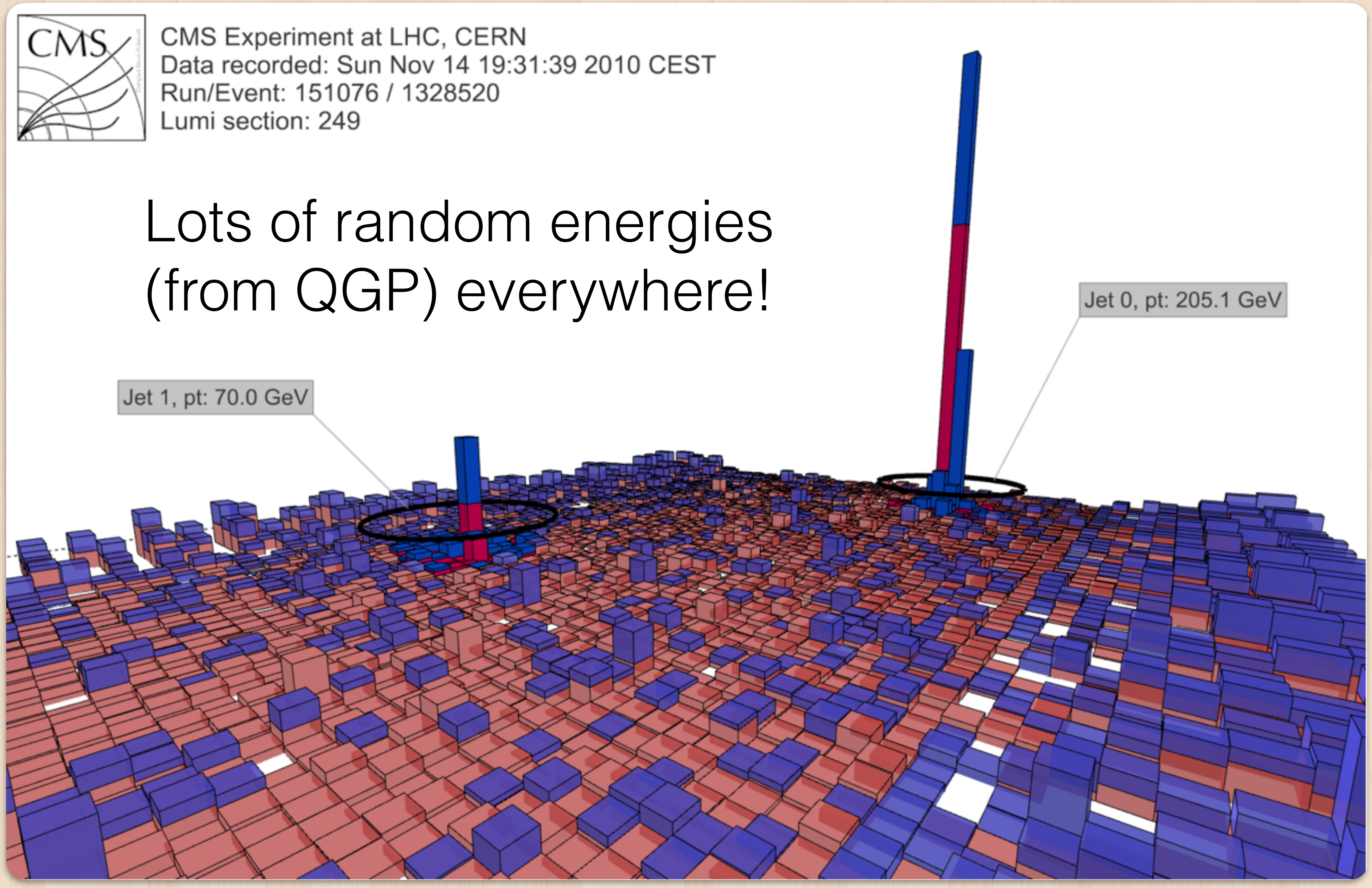
Submerging into the QGP



What will happen?

Key difference to no-QGP case:
space-time structure of jet evolution now matters

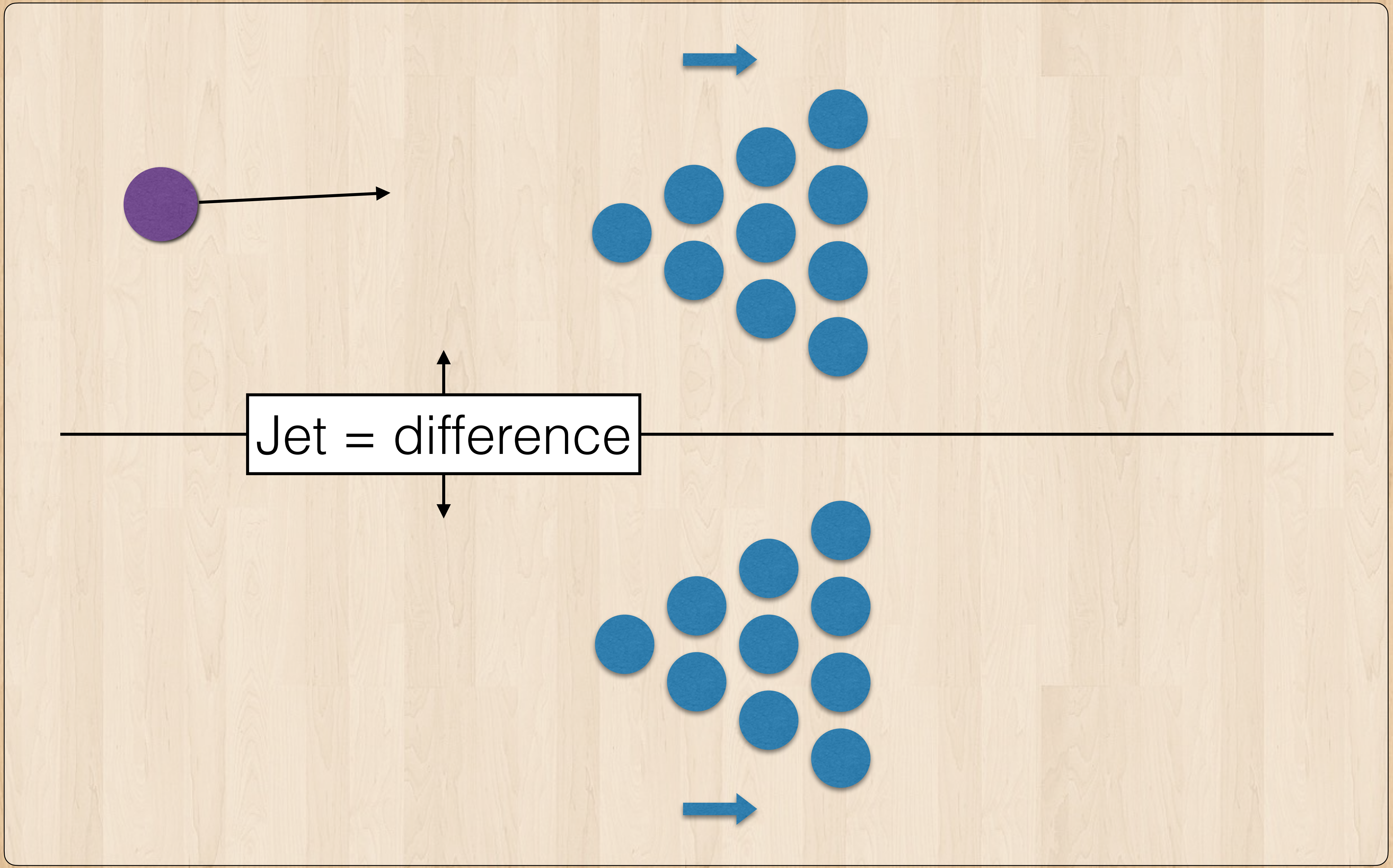
Example jets in collisions



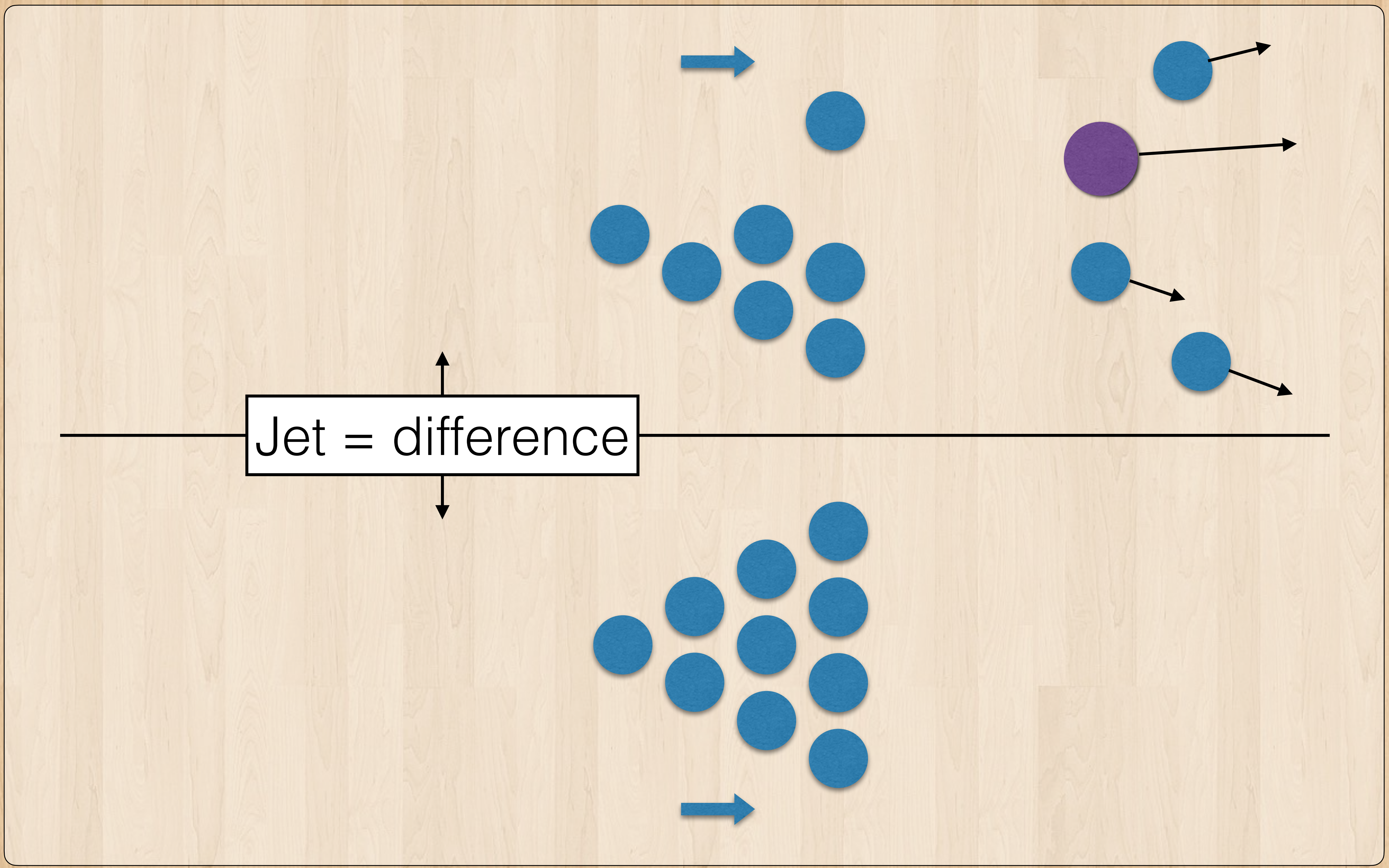
How do we define jets?

- Using the same algorithms gives a lot of extra unrelated energy from the QGP
- The current paradigm is to somehow remove them from the jets
  - A bit tricky for complex observables
- One way to define it: the “net effect” of the high energy parton

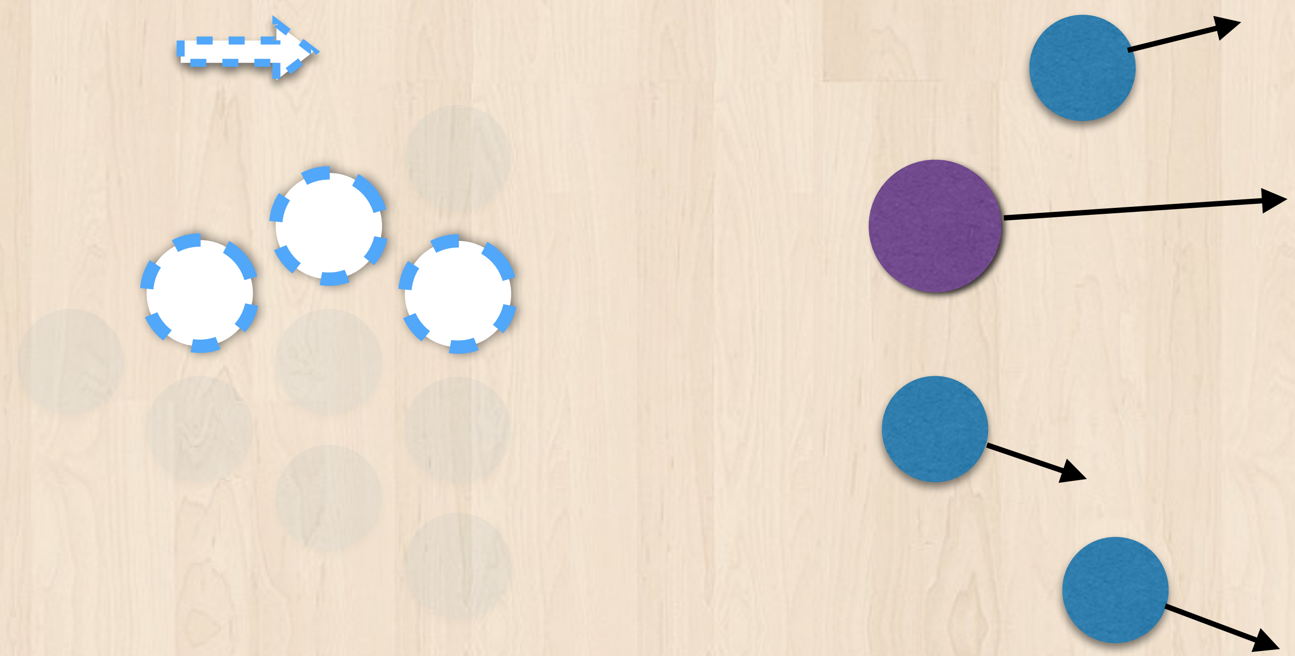
Before

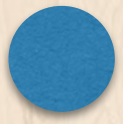
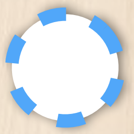


After



Difference



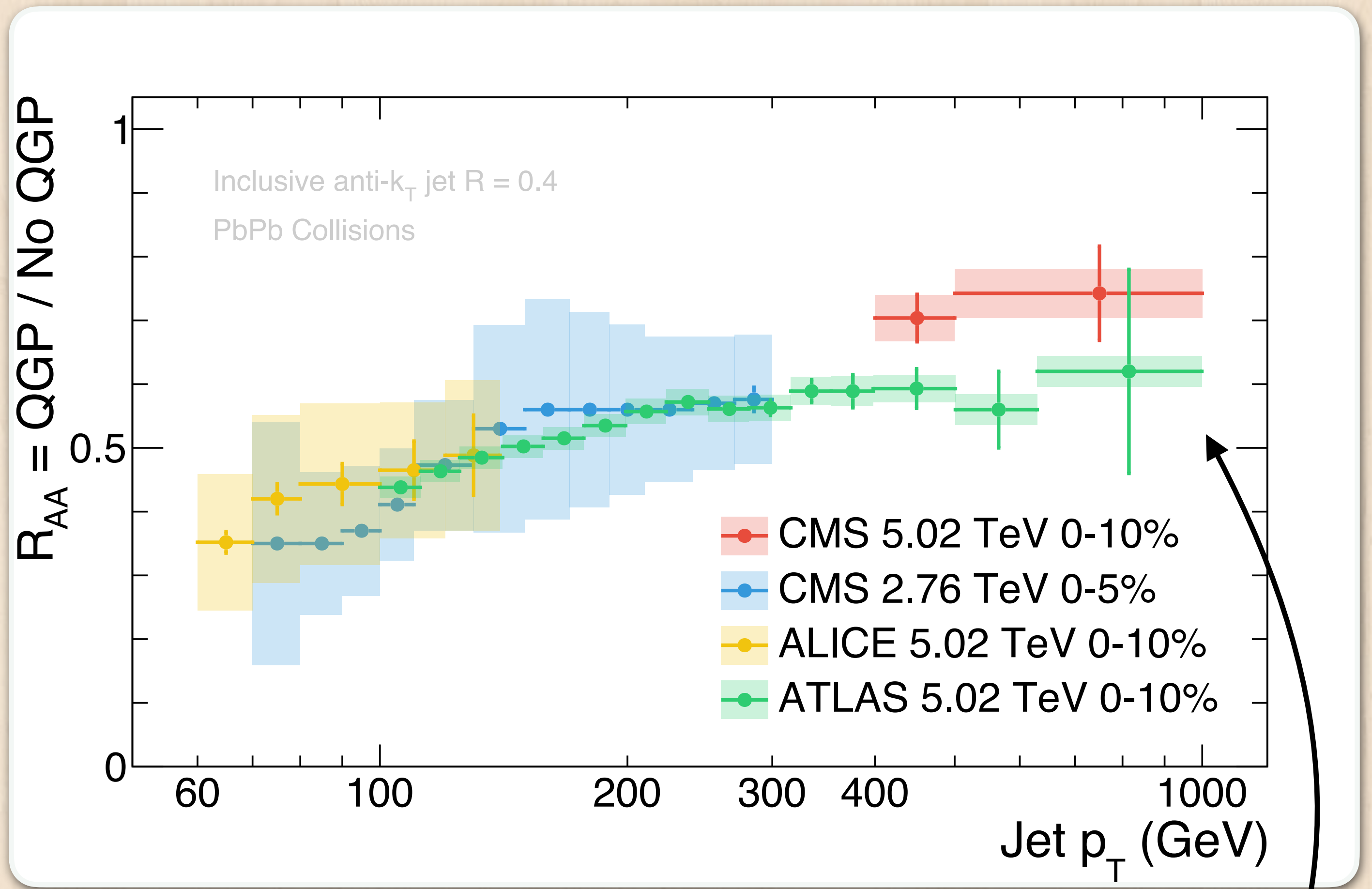
Jet =  +  - 

Again on the definition of jets

- Similar to vacuum, jets are defined by algorithms
- In this picture, part of QGP that happens to be in the same direction of jets is not part of the jet
- Experimentally we need dedicated background subtraction algorithms
    - In the current paradigm, subtraction algorithms are *not* part of the jet definition
    - We assume that physics result stays invariant

What do we know about them

Jets are suppressed



"Nuclear modification factor":

$$\frac{\sigma \text{ with QGP (PbPb)}}{\sigma \text{ without QGP (reference)}} \sim 0.6 - 0.7$$

1000 GeV = 10^6 MeV

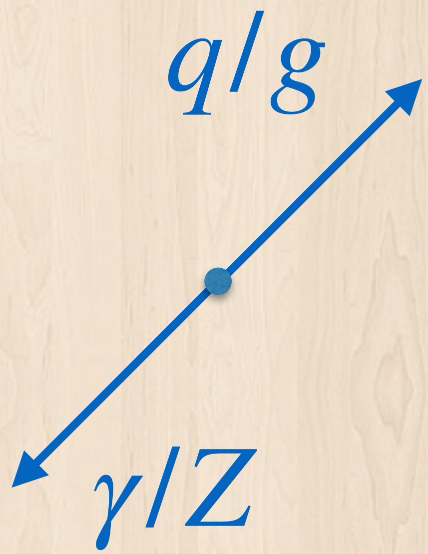
$T_{QGP} \sim 160 - 500$ MeV

>1000x

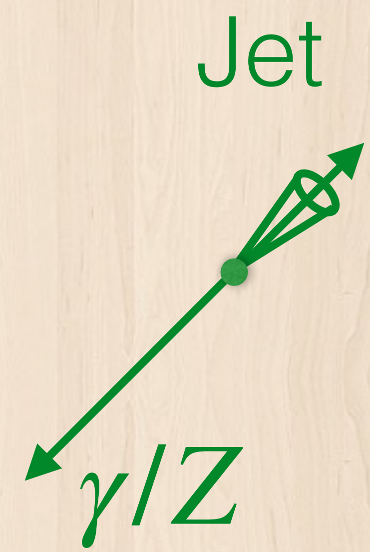
A lot fewer jets!

"Jet quenching"

How to see if jet energy changed?

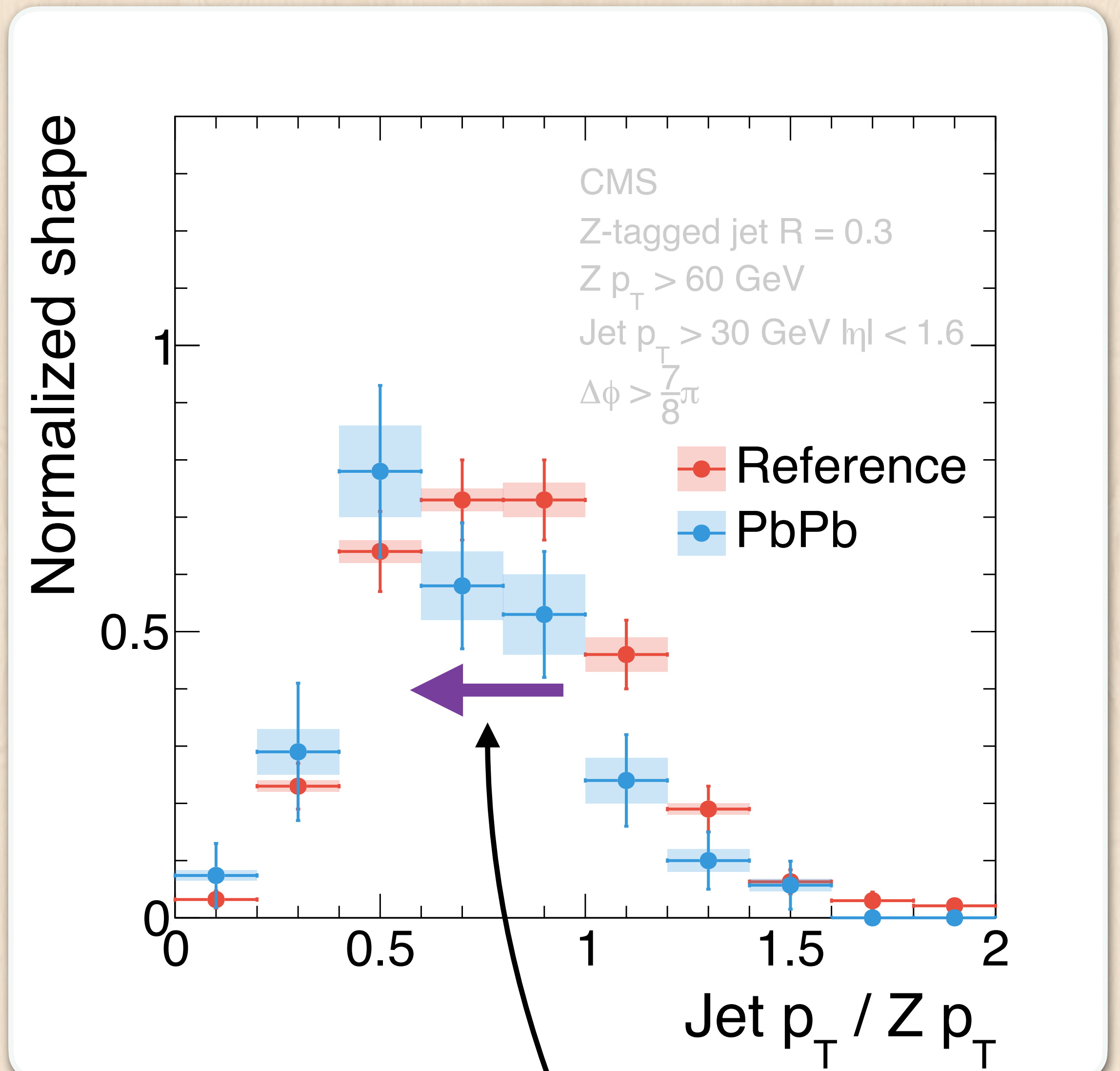


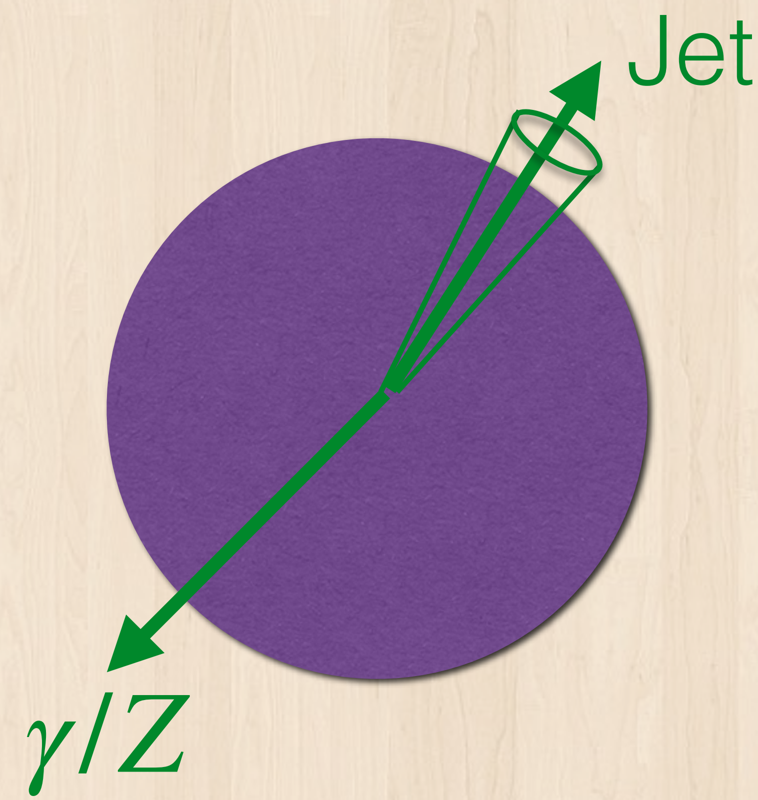
Before QGP
Momentum ~balanced



After QGP
Photon momentum remains the same

Jets lose energy

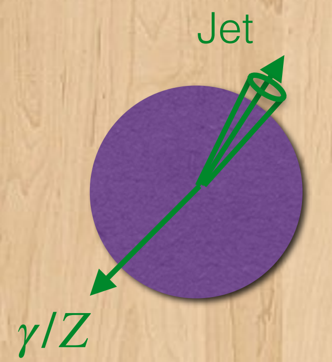




Mean of the distribution drops from reference to PbPb

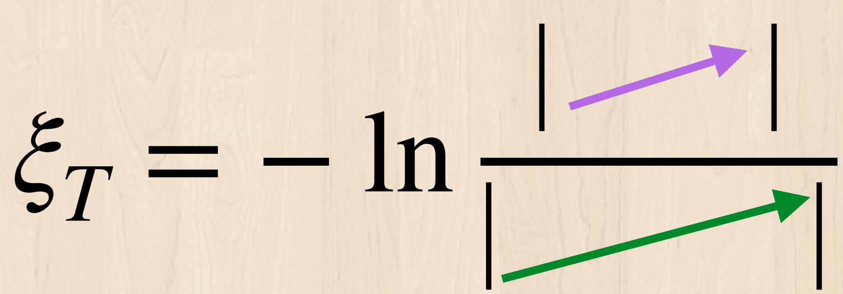
Jets are losing energy, like 10-20% on average

PRL 119 (2017) 082301

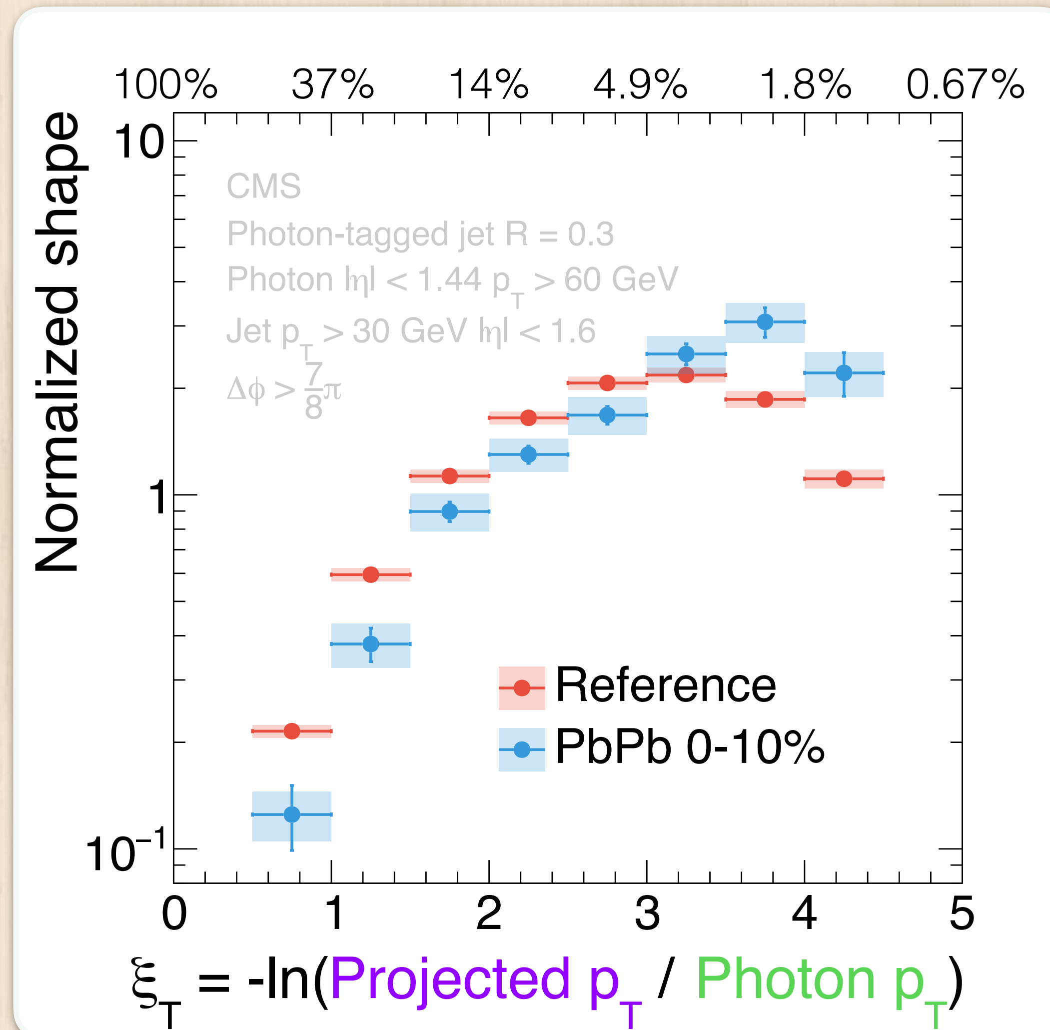


Particle distribution

Photon p_T ~ initial q/g p_T

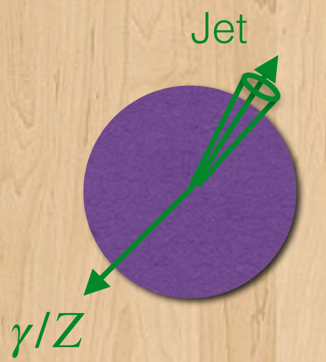


Hard ⟵⟶ Soft

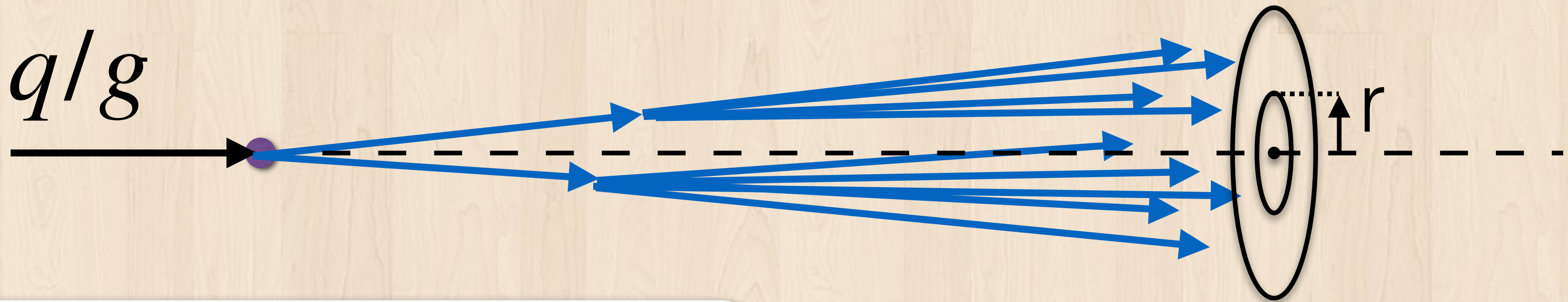


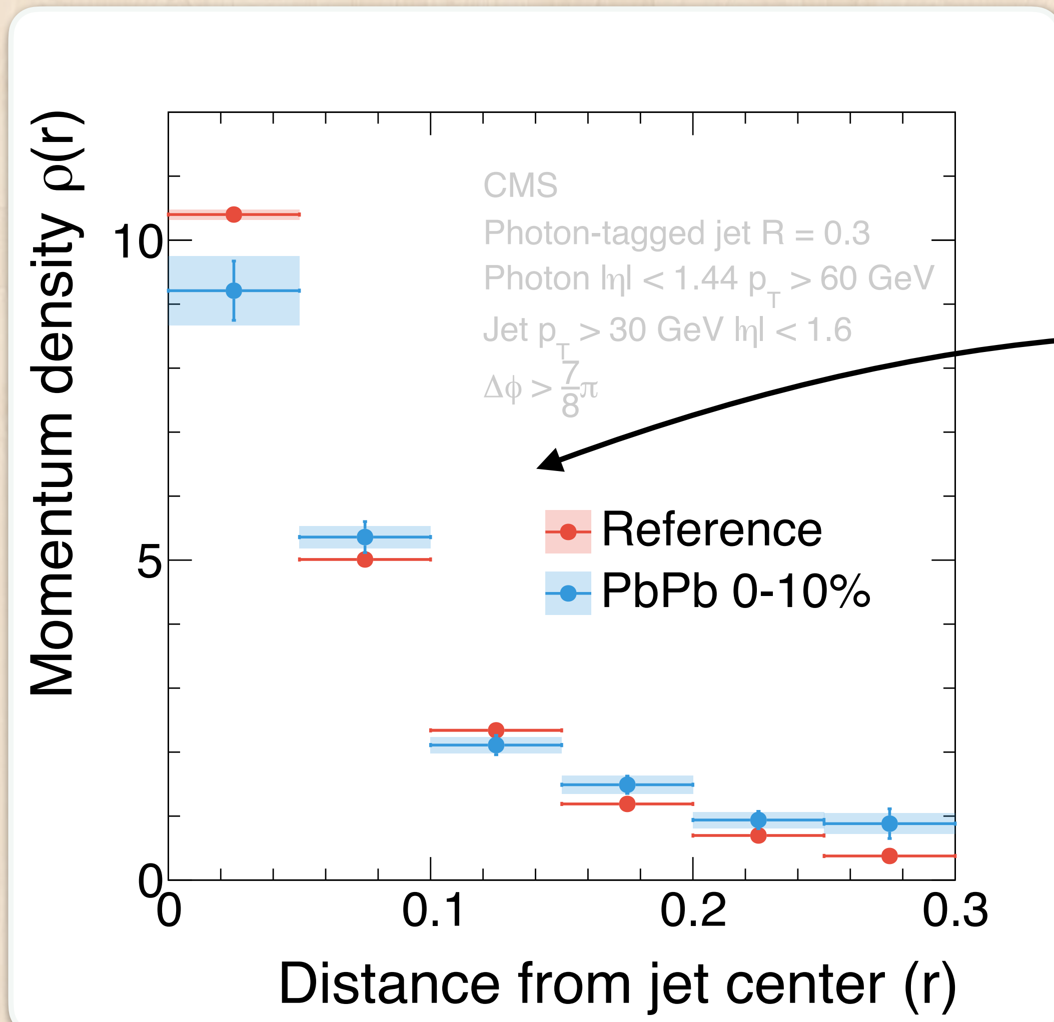
In PbPb we see a lot more soft particles in the jets

PRL 121 (2018) 242301



Radial distribution



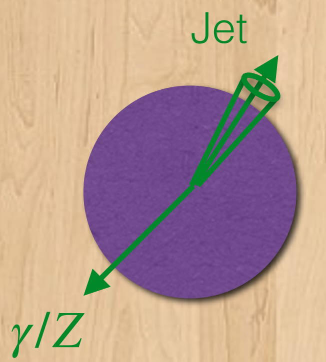


Energy in jets are concentrated in a small area on average

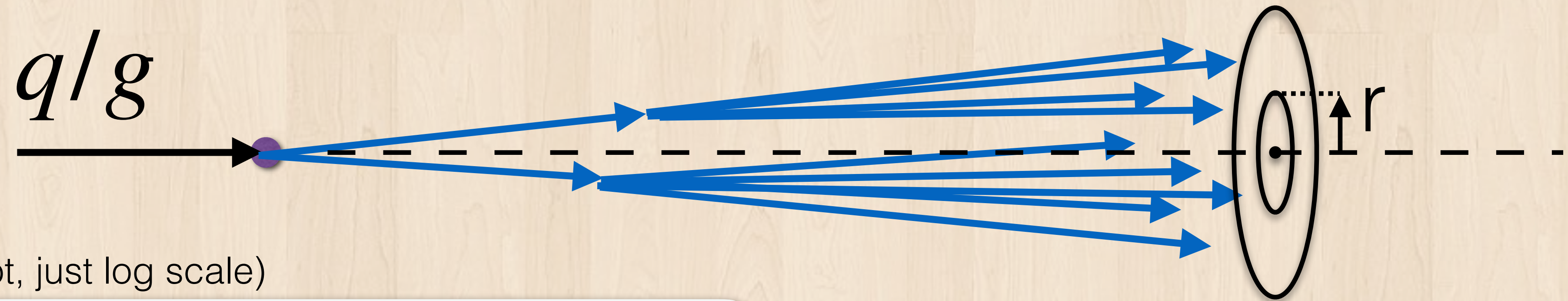
Larger tail observed in jets in PbPb

Energy is pushed away!

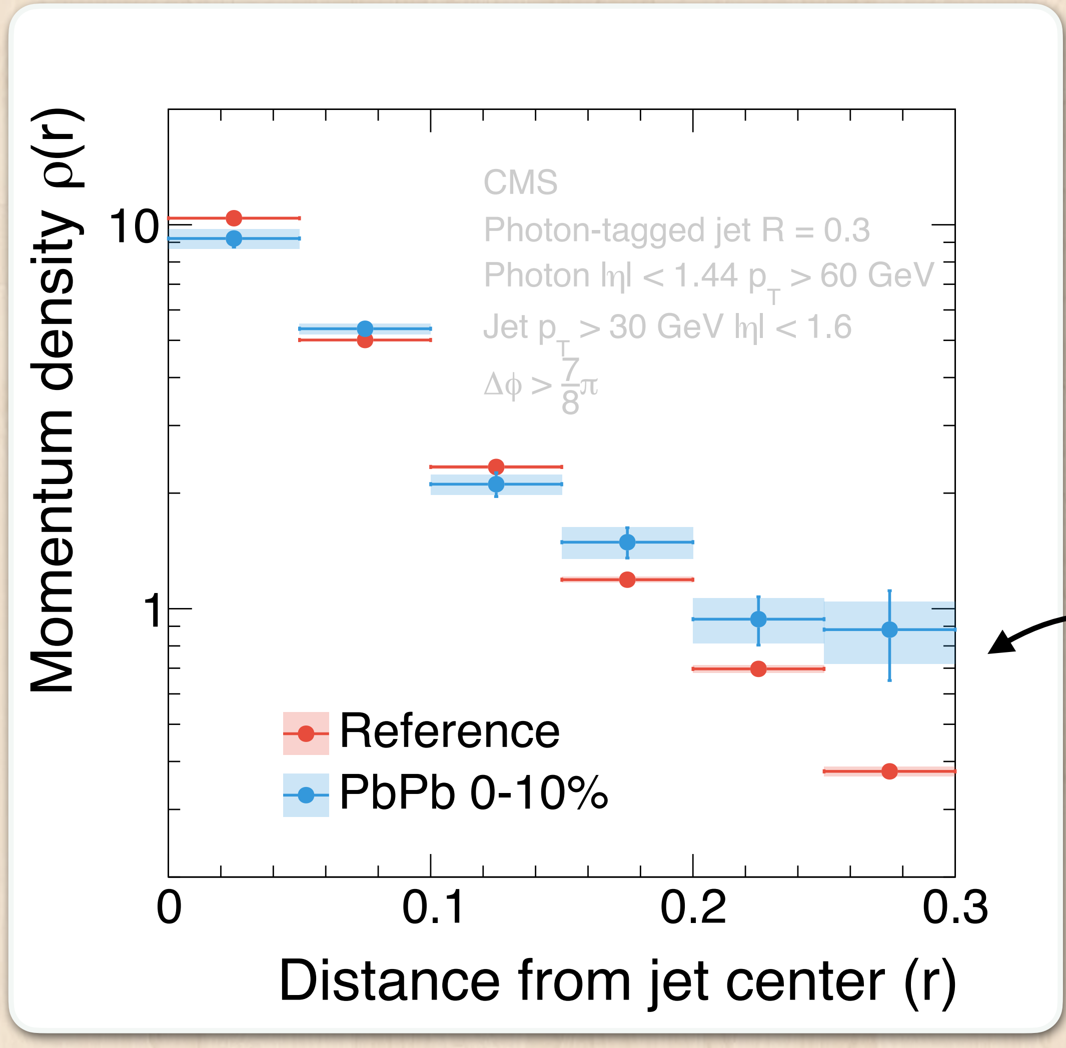
PRL 122 (2019) 152001



Radial distribution



(Same plot, just log scale)



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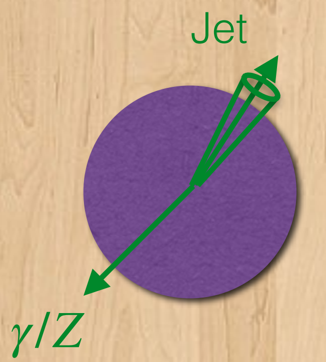
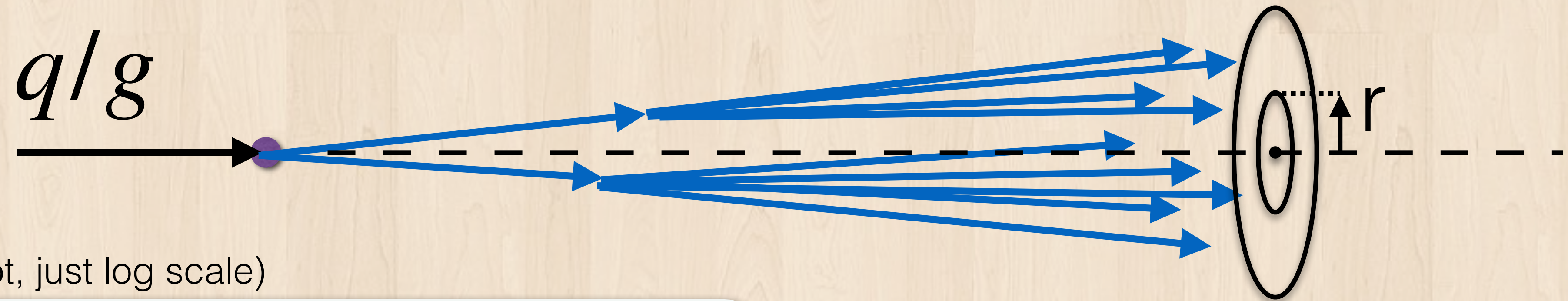


Radial distribution



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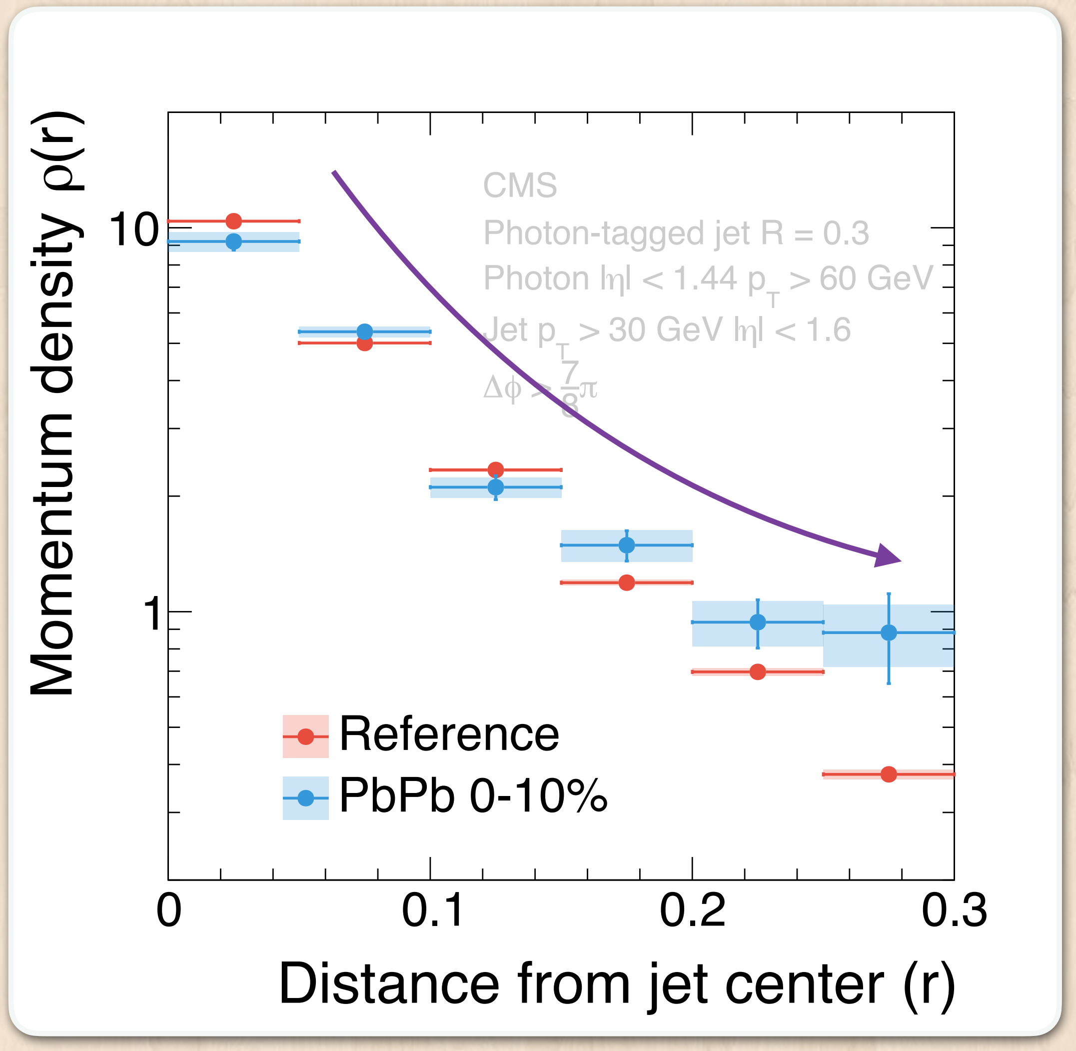
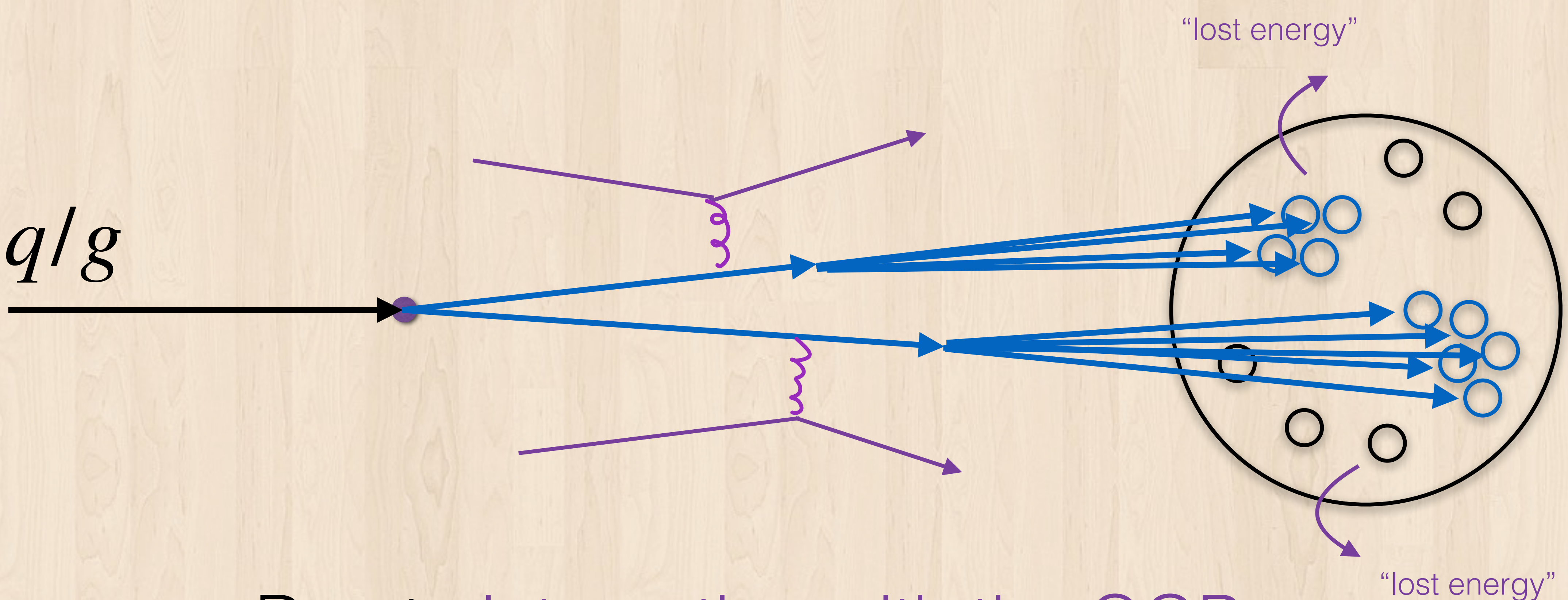


Energy in jets are concentrated in a small area on average

Larger tail observed in jets in PbPb

Energy is pushed away!

So what happened?



Due to interaction with the QGP
energy is transported away from jets
a lot more lower energy particles all over the place

Distribution sensitive to interaction mechanism
For example radiative vs collisional energy loss

So what happened?

Du

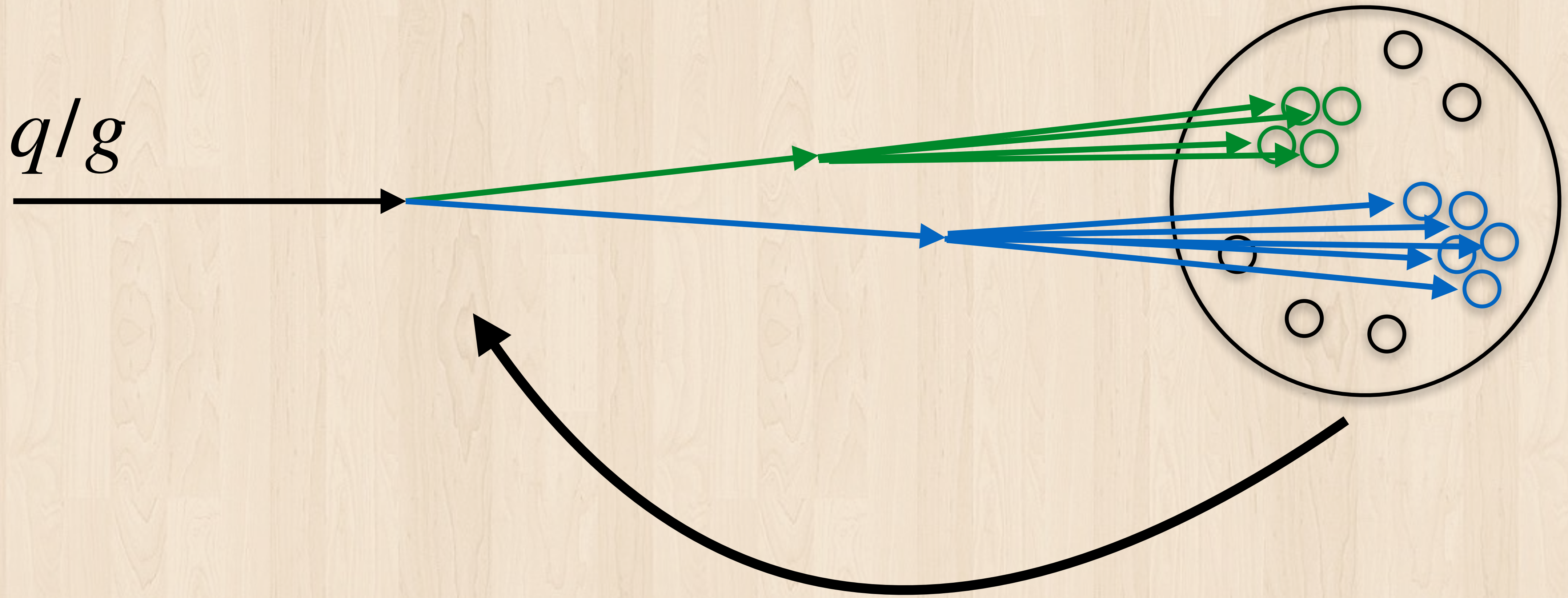
energ … jets

a lot more lower energy particles all over the place

Distribution sensitive to interaction mechanism
For example radiative vs collisional energy loss

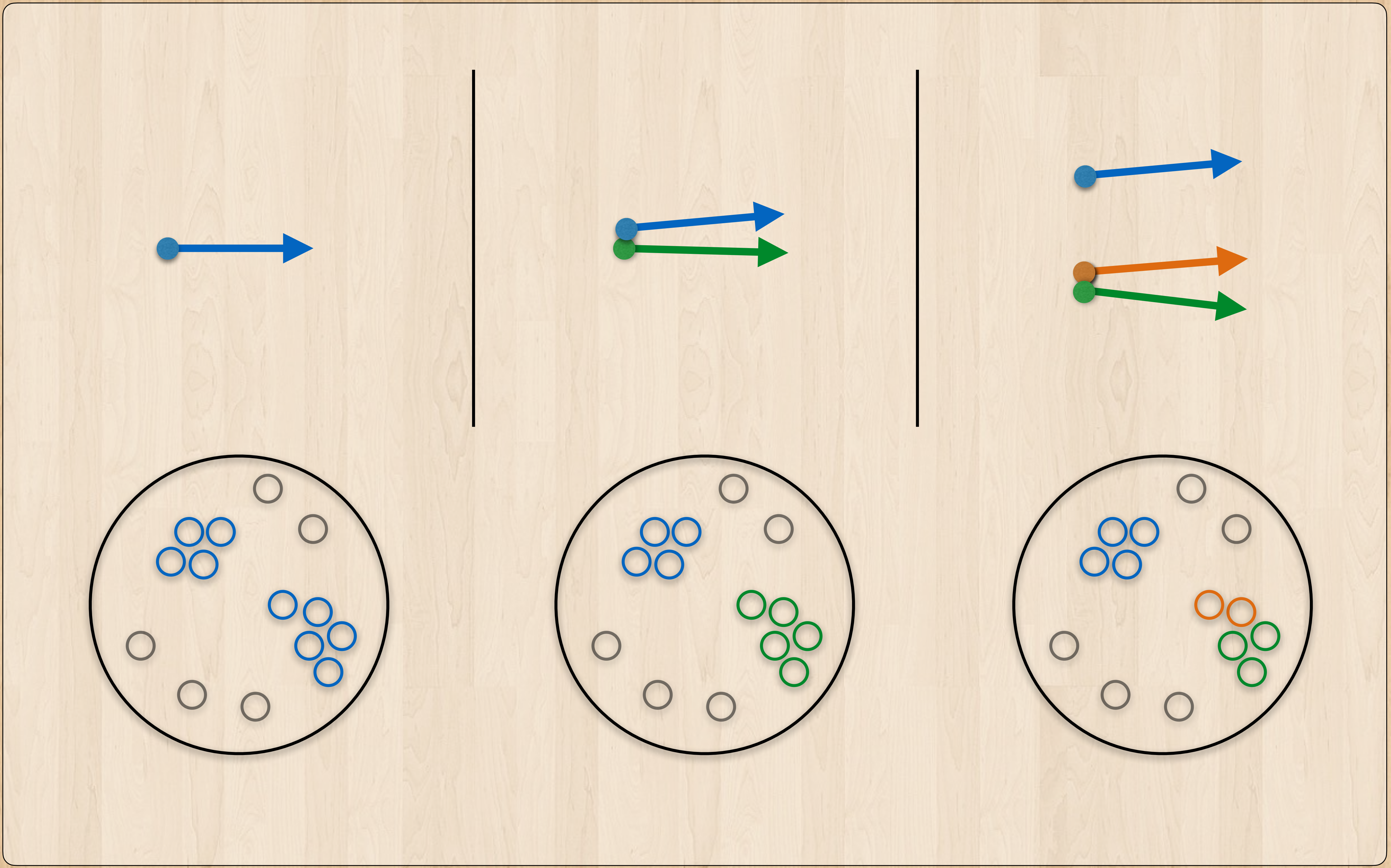
Using jets as a tool

Particles are not uniform

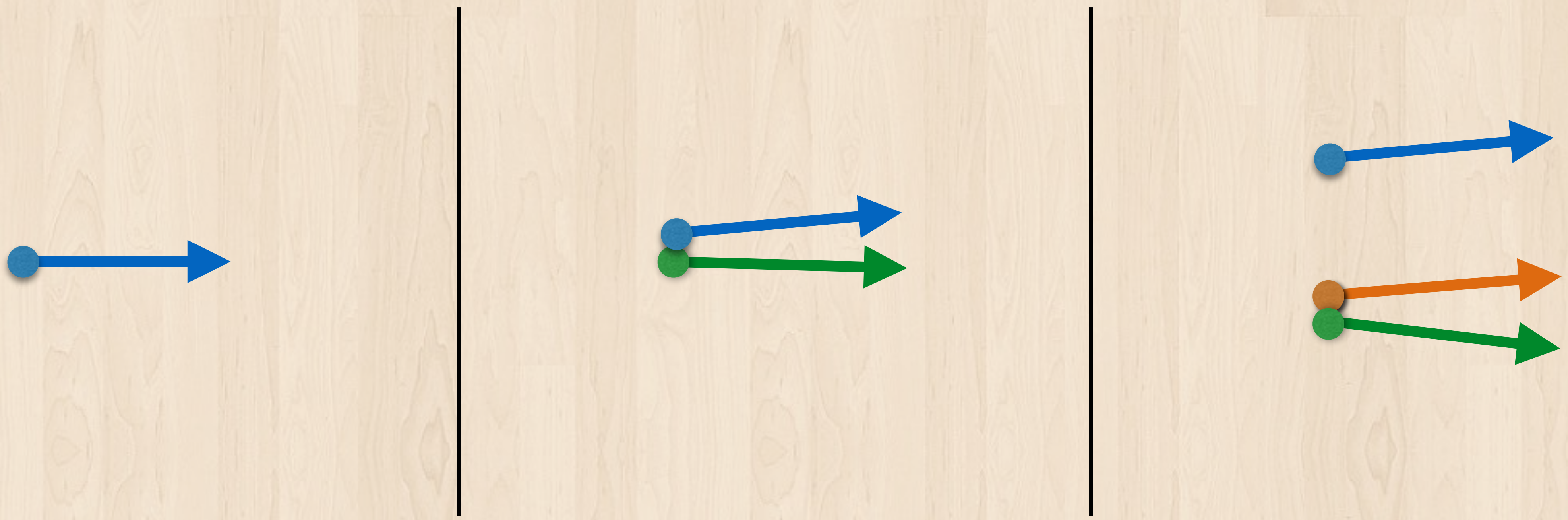


From final particles in the detectors we can infer evolution properties

Tracing through the history



Tracing through the history

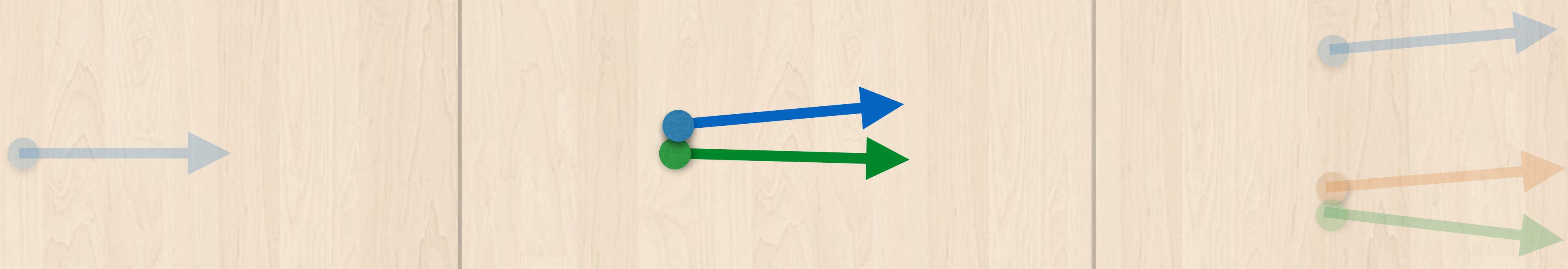


1 particle

2 particles?
1 group?

3 particles?
2 groups?
...

Tracing through the history



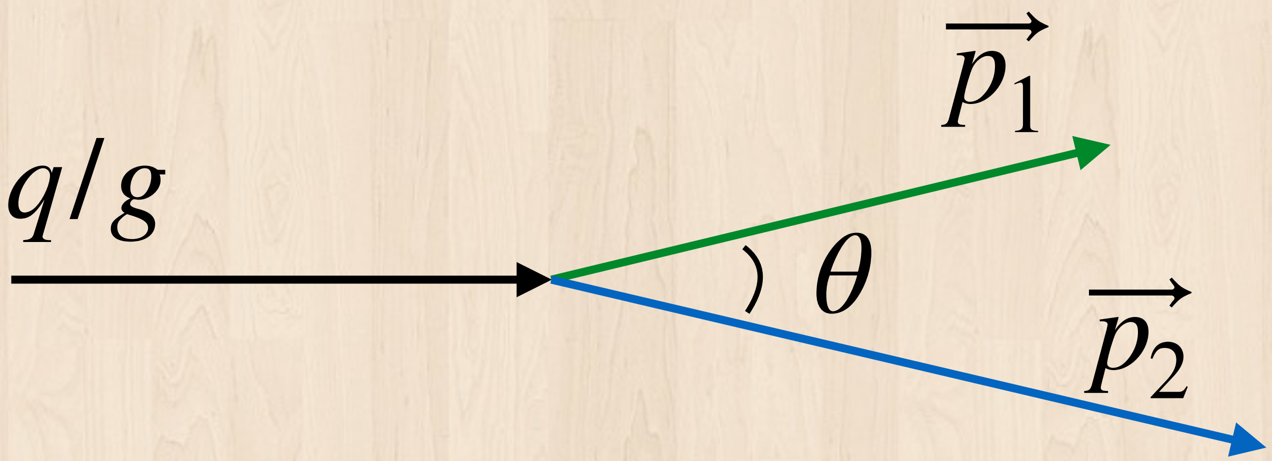
1 particle

2 particles?
1 group?

3 particles?
2 groups?
…

Let's focus on this case

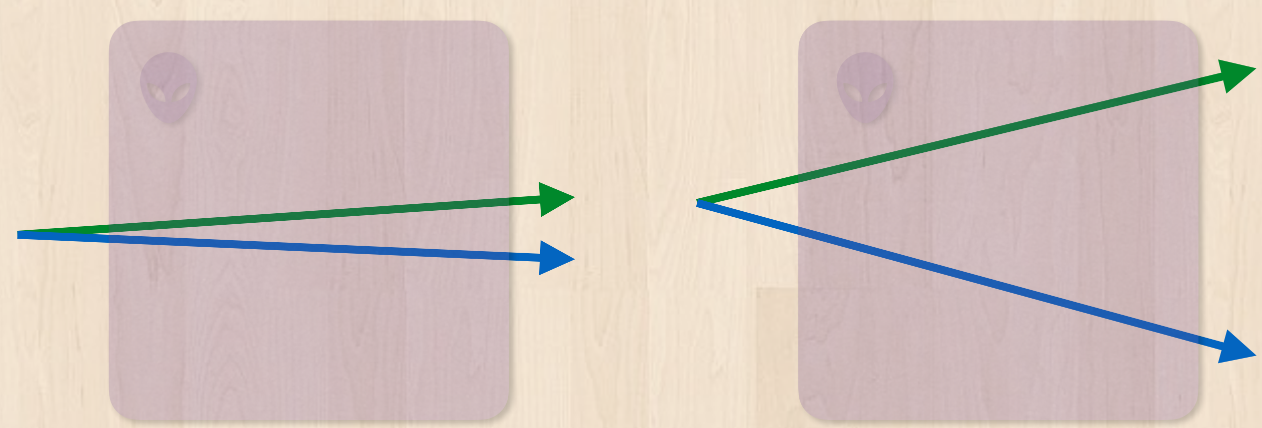
Using the pair to probe things



Already many interesting things to study

For example… is there a **resolution scale** in QGP?

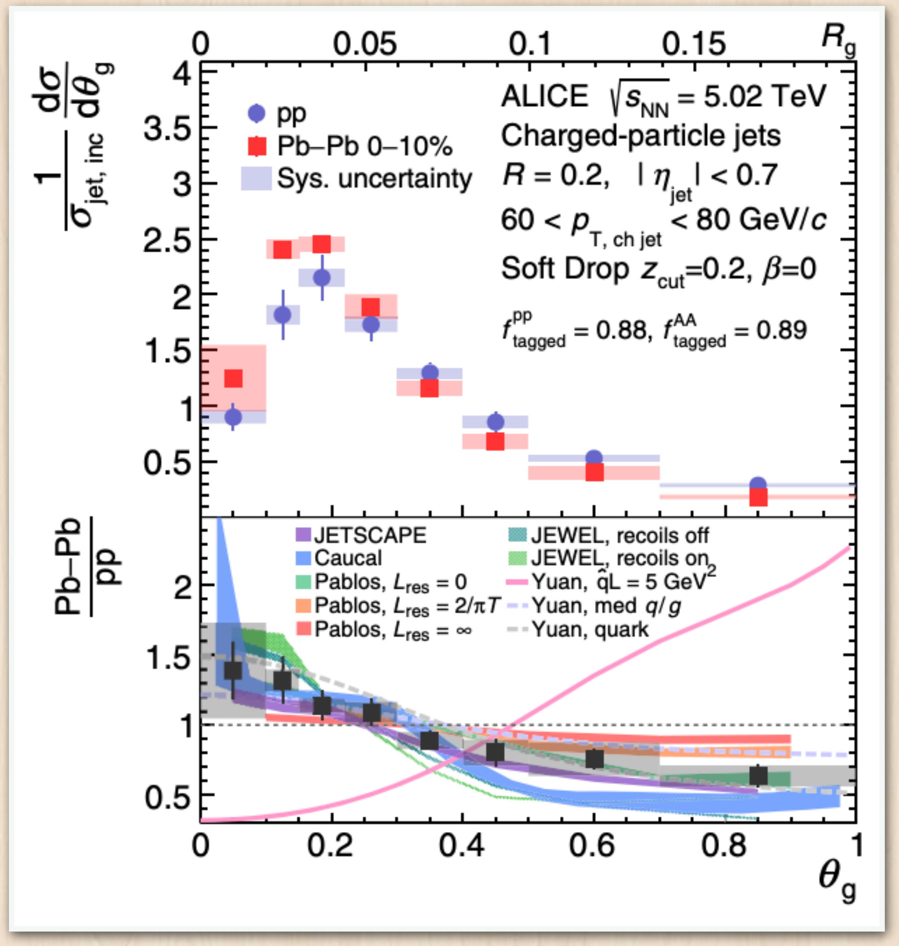
Idea: If things are too close to each other QGP might not see them as separate objects

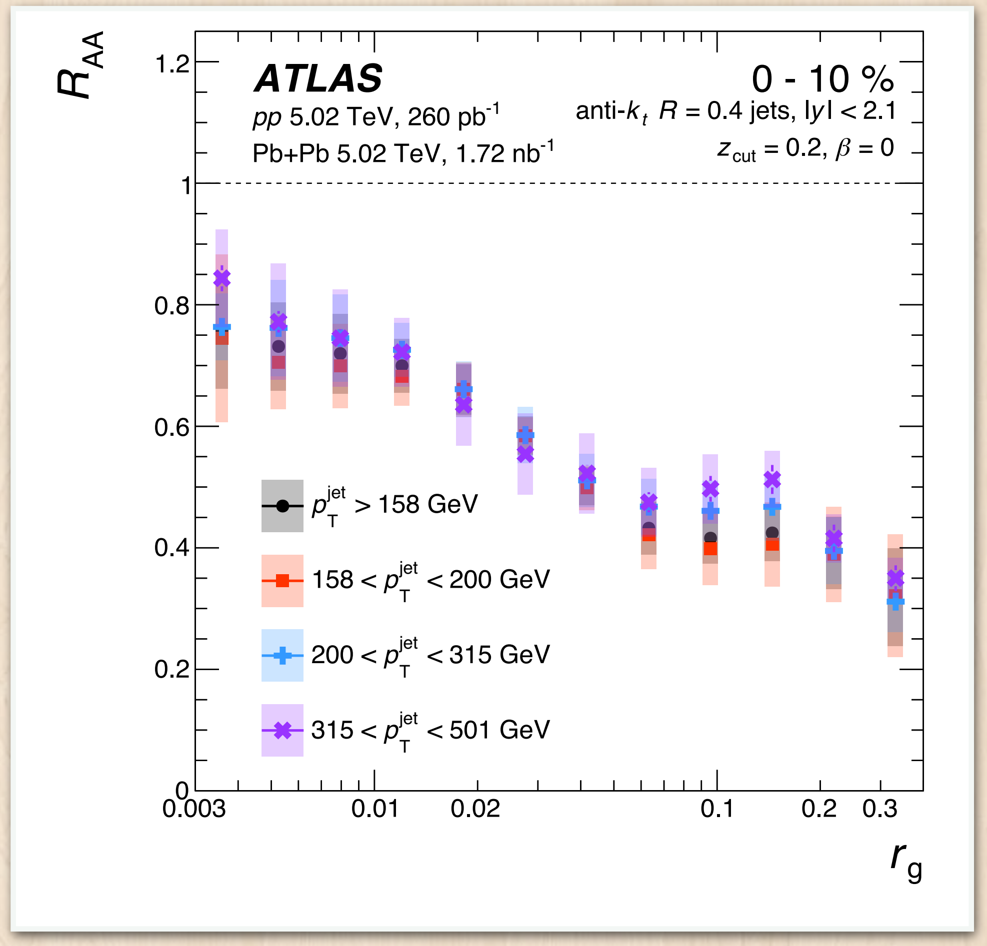


Less interaction

More interaction

Angles



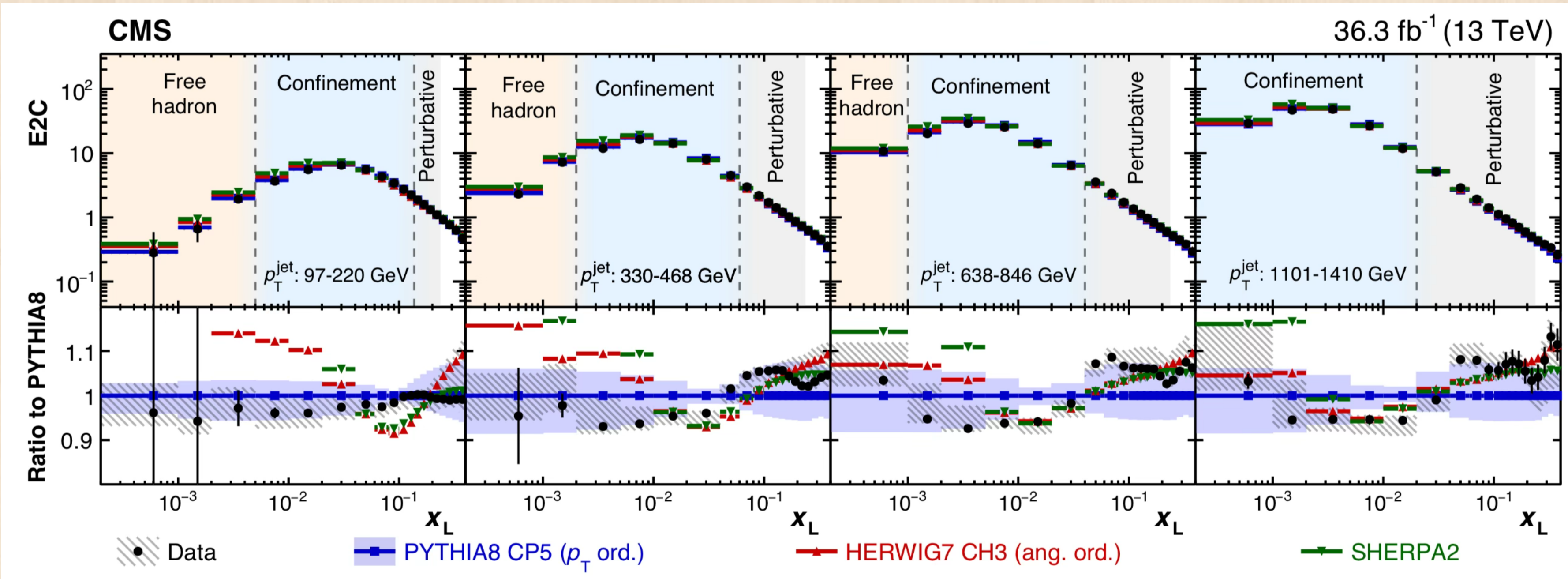


$\theta_g = r_g / R_{jet}$

Jets with large angle structures are more suppressed!

Though no clear "turn on" point so far

Energy-energy correlator



$$E2C(x_L) = \sum_{i,j} \frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2}\, \delta(x_L - x) \quad \ldots\ldots$$

Renewed interest in recent years

Different regions with different dominant physics

Measure α_s, probe QGP effect, …

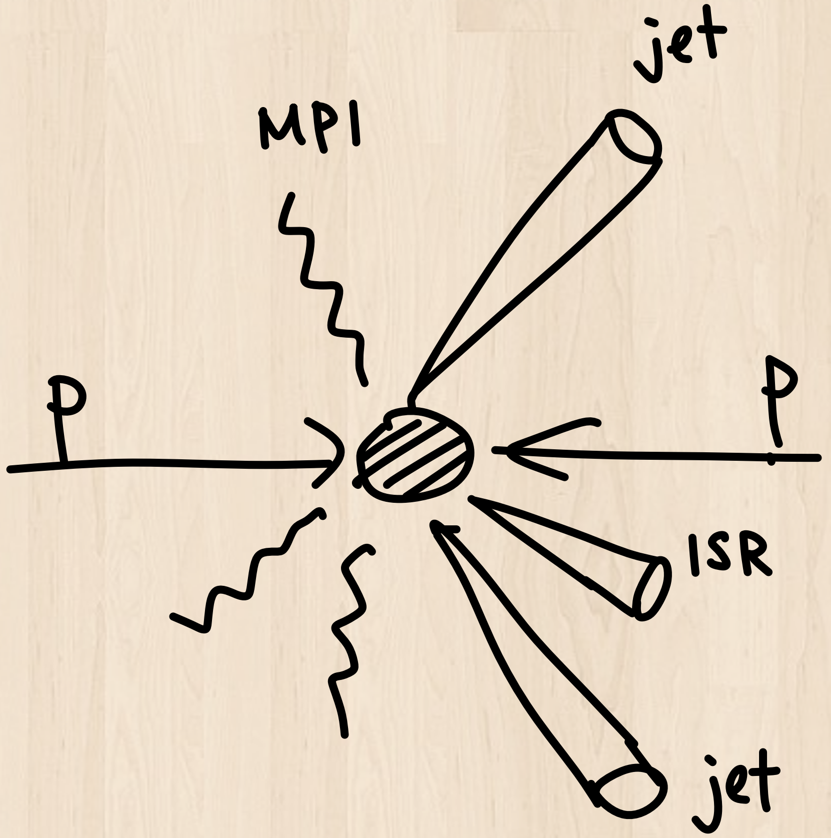
Jets in EIC

Jets in EIC

- Jets are proxies for quarks/gluons
- Important tool in EIC
  - Much cleaner than hadronic collisions: precision QCD measurements
  - Nuclear PDF
  - Nuclear modification of jets
  - Studying helicity-dependent PDFs
  - …

Precision QCD measurement

- EIC provides a much cleaner environment compared to the hadron-hadron collider results
  - We see everything!
- Great for performing precision QCD measurements



PDF convolution
No longitudinal control
More ISR
MPI

Cold nuclear effects

Jets can interact with the nuclear matter
→ (cold) nuclear modifications

Jet charge

Cross section

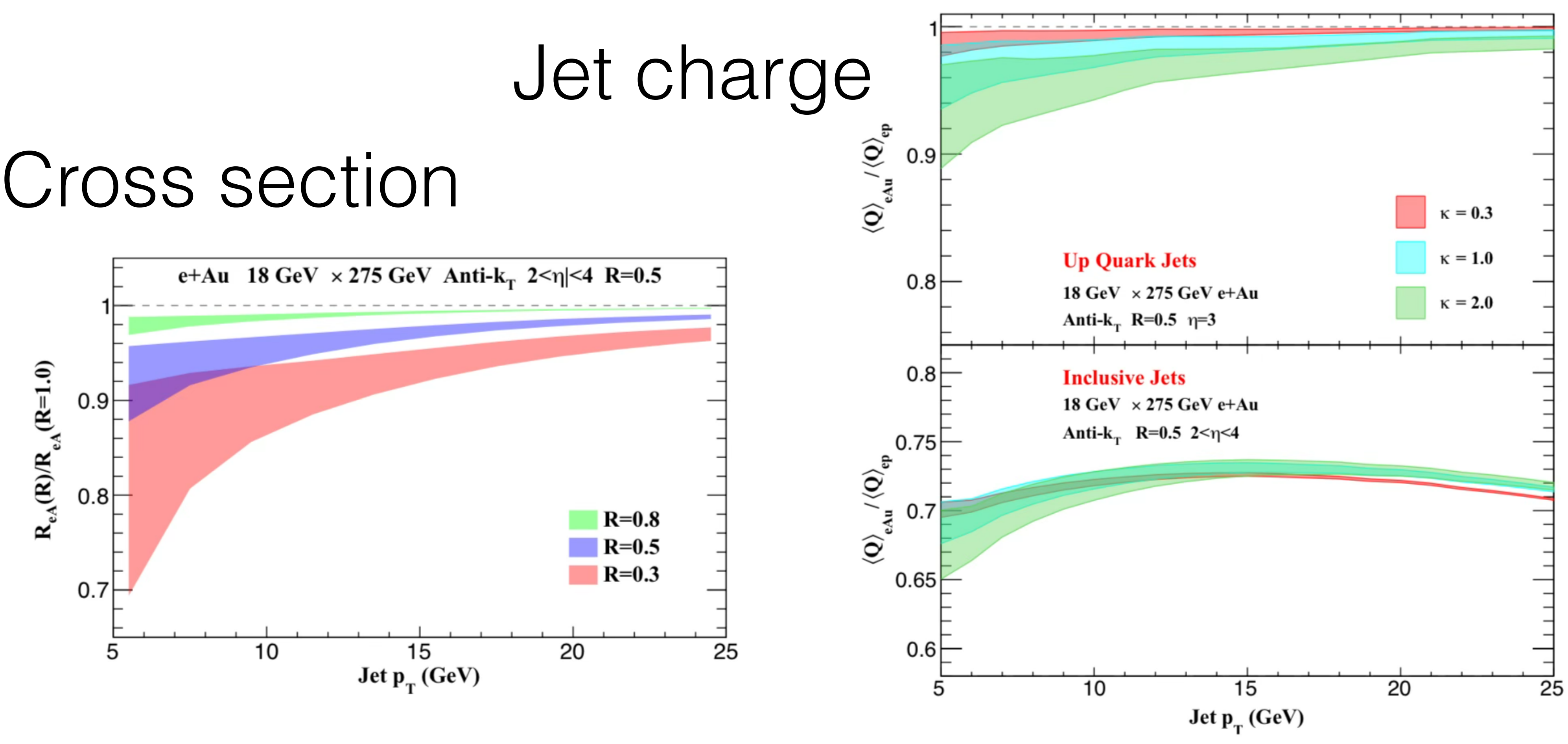
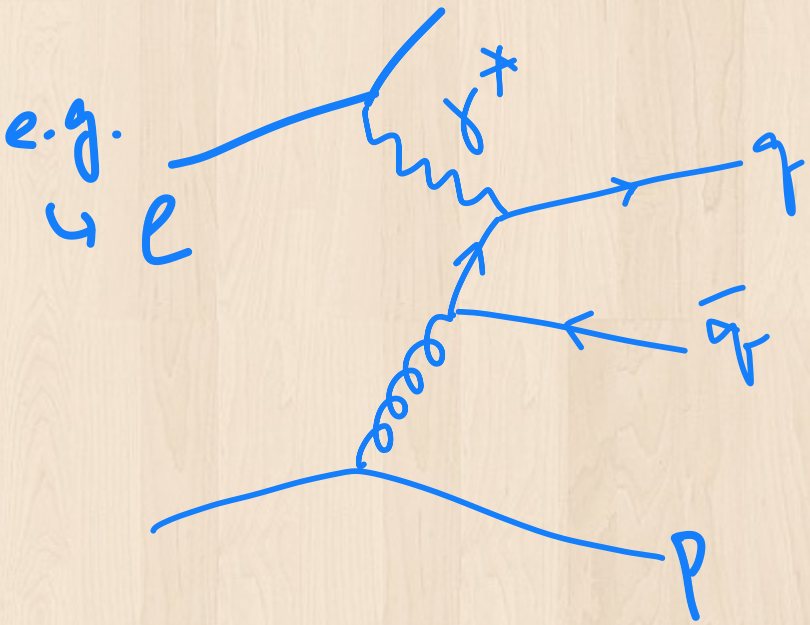


FIG. 35. The left plot shows the ratio of jet cross section modifications for different radii. The right plot presents the modifications of the jet charge in e+Au collisions.

EIC white paper arXiv 2203.13199

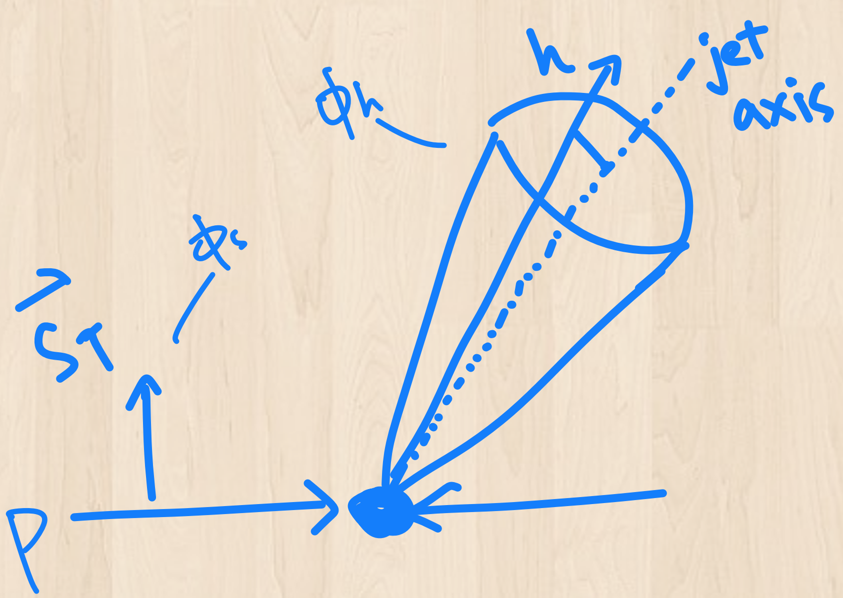
PDFs with jets

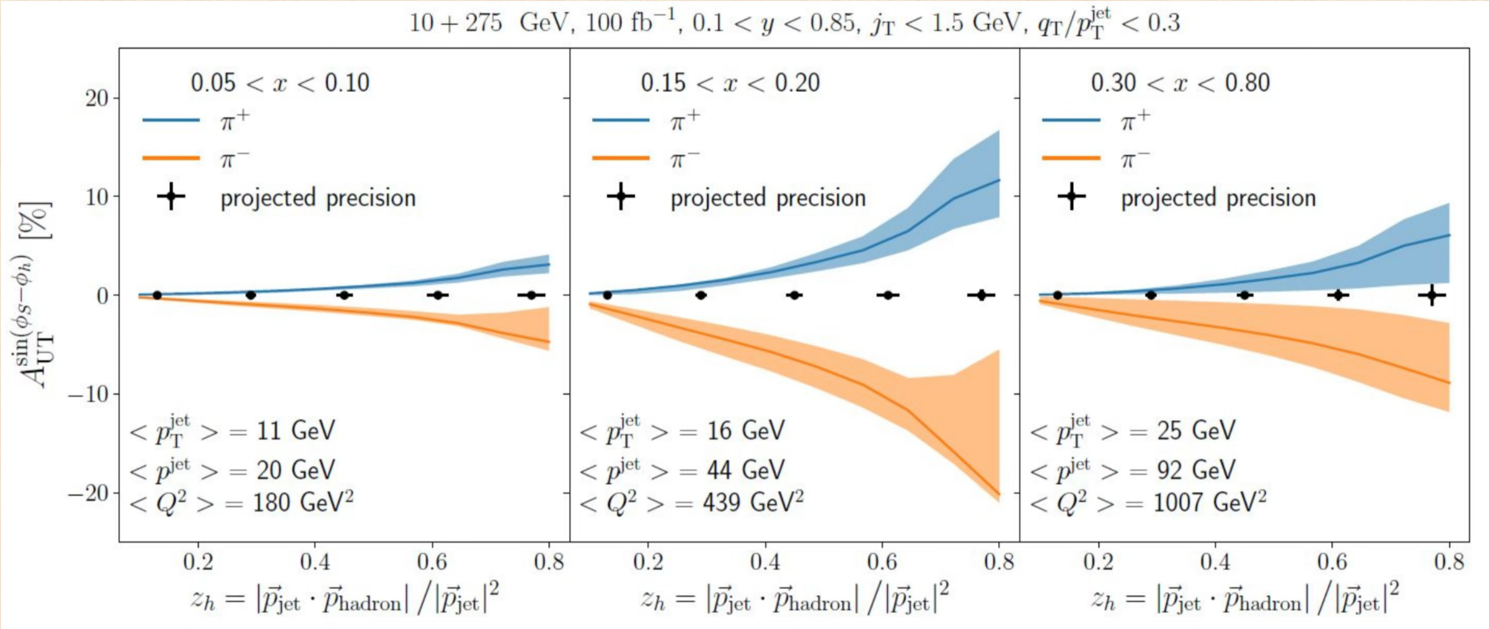
- As usual we can study the collinear PDFs
  - Probing low-x
- Helicity dependent PDFs: through polarized beam
  - So far large errors, EIC expect to improve this
- Sensitive to TMD PDFs
- (…and a lot more!)



Looking inside jets

- A lot of information to learn from inside jets
- Example: hadron-in-jet azimuthal asymmetry
- Polarized quark inside a polarized nucleon => azimuthal asymmetry





Concluding remarks

Jets: wrapping up

- Highly virtual partons shower into jets
  - Jets are **proxies for partons**
- Typically a bunch particles **concentrated in small area**, lots of **soft particles**
- **Jet quenching** effect in QGP: energy gets pushed away from the center of the jet
- **Not point-like**: contains a lot of information = gold mine
- Versatile tool in both hot and cold QCD (also some crazy people are measuring them in e^+e^- :))

Backup Slides Ahead