Measurement of electric charge dependent splitting of directed flow in STAR experiment at RHIC

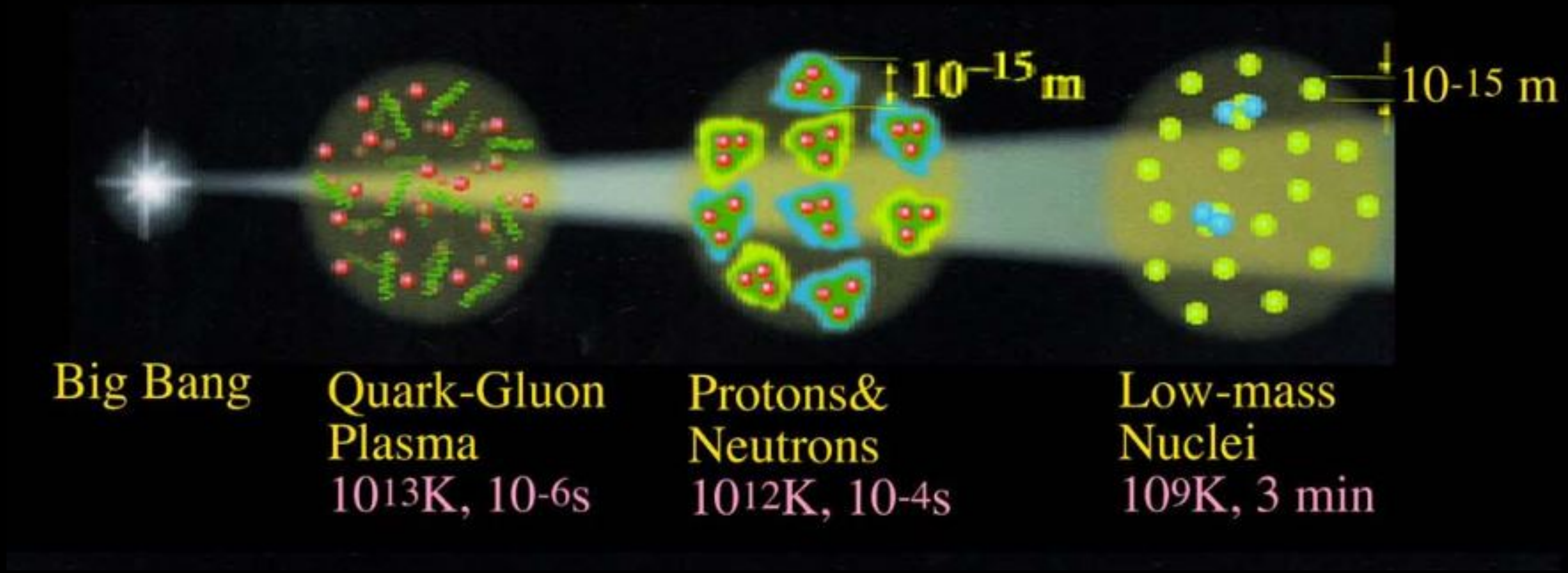
Ashik Ikbal (Kent State University)

Részecskefizika Seminar
Department Of High Energy Physics, Wigner Research Centre for Physics
Hungarian Academy of Sciences

Budapest, Hungary, May 30, 2022

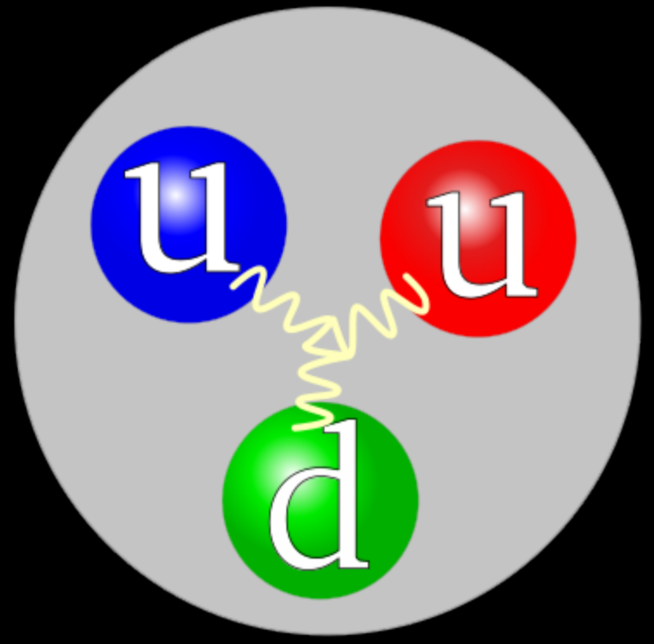
Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

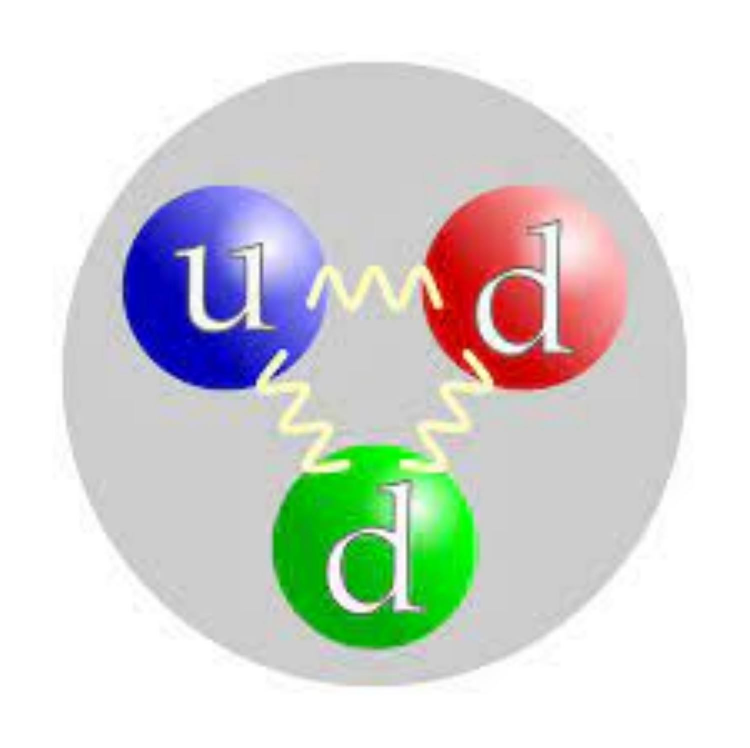
Quark Gluon Plasma (QGP)



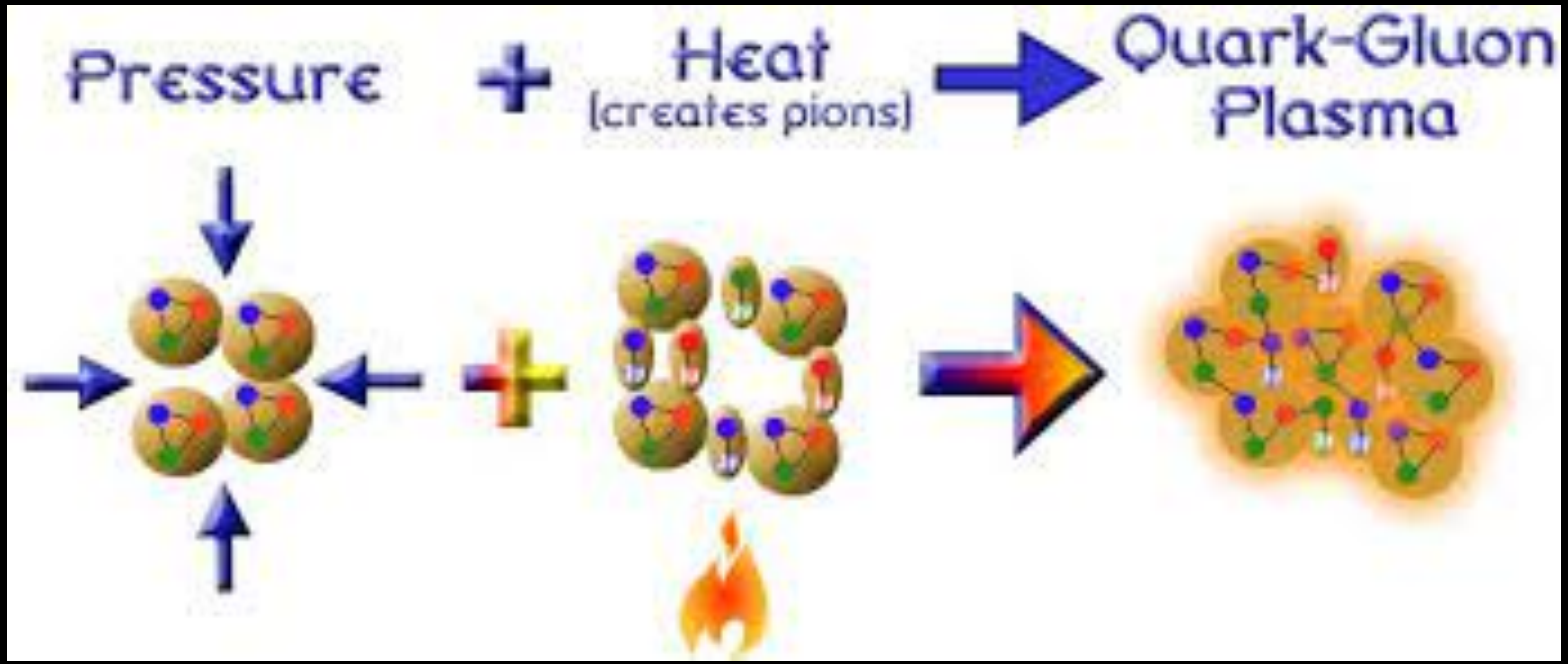
- A few microseconds after BigBang, the universe consisted of a hot soup of quarks and gluons
- Later on the universe began to cool down — then nucleons, low mass light nuclei and eventually the matter around us are formed
- The deconfined state of quarks and gluons, existed in the early universe - Quark-Gluon Plasma (QGP)
- To understand early universe => Need to study QGP

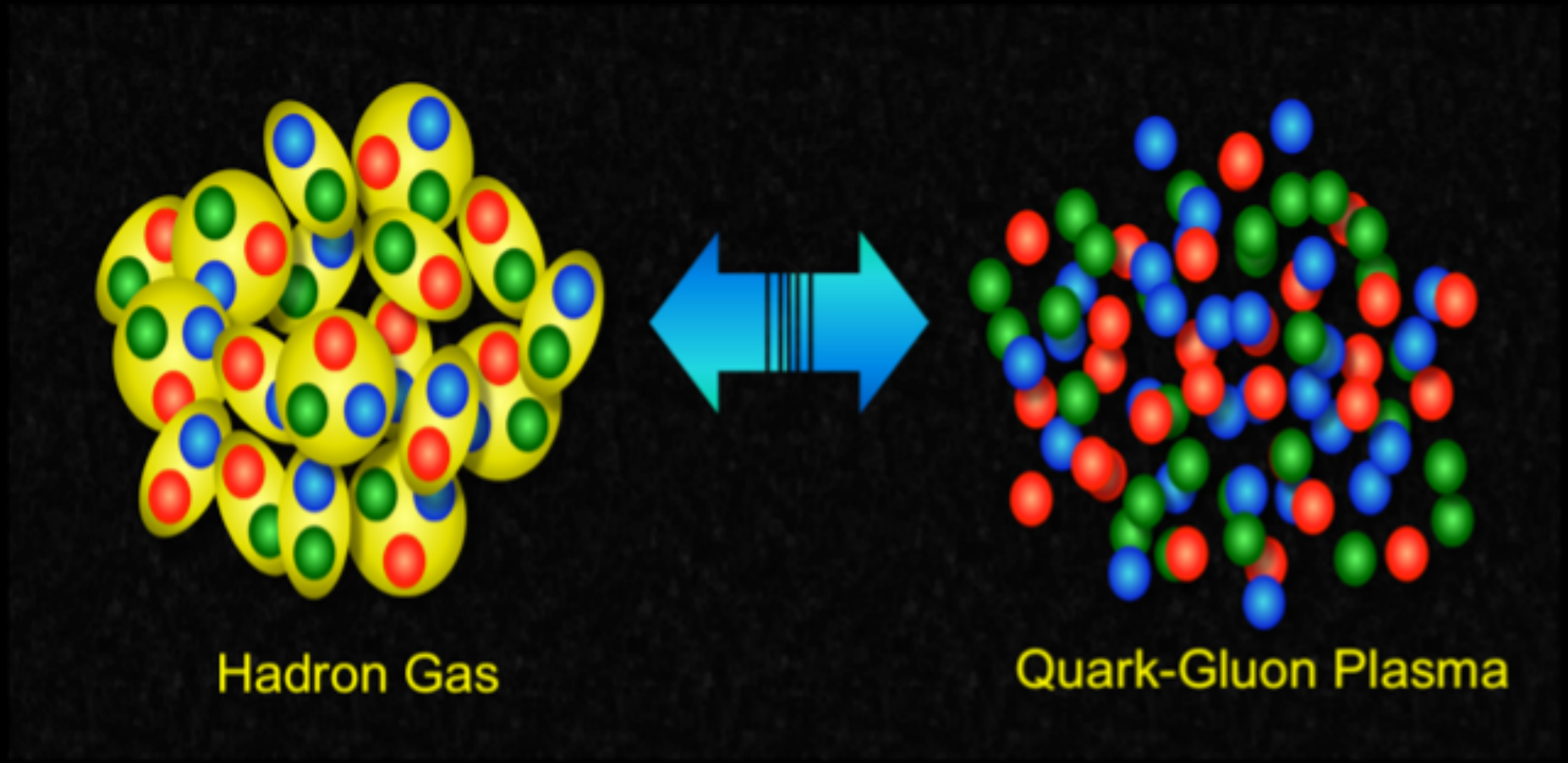
How to create QGP ?





- Quarks and gluons are confined inside hadrons - How do we deconfine them?
- Certain conditions like extremely high pressure (P) and temperature (T) can deconfine them





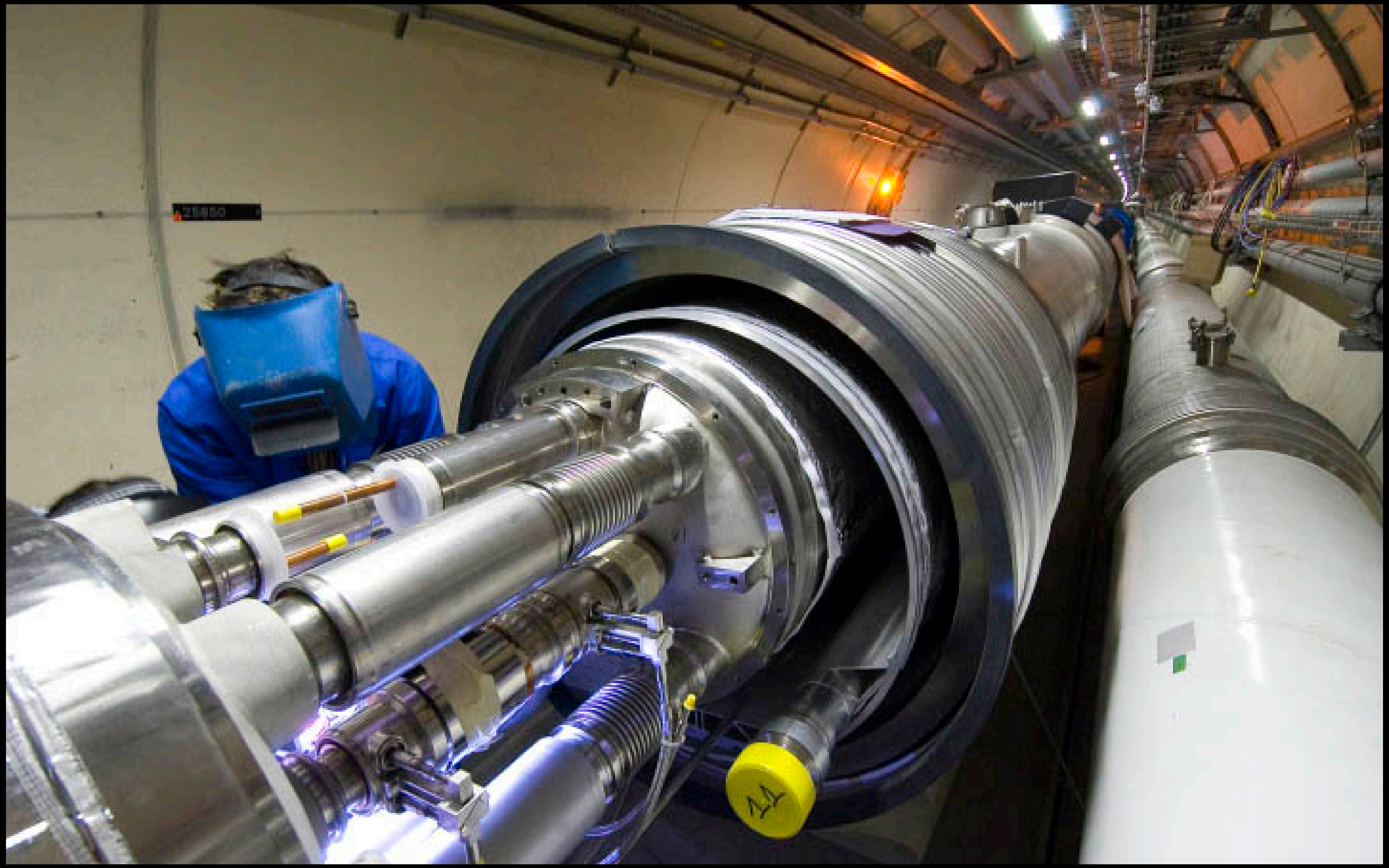
- Under such conditions, the hadrons get close to each other so that quarks and gluons inside them can fly around freely in an extended volume
- Hadrons to QQP transition takes place at T ~ 10^4 times temperature of the core of the sun
- Big particle collider produces such extremely high T for a short period of time by colliding ions at relativistic energies

Relativistic colliders

Relativistic Heavy Ion Collider (RHIC) at BNL

Energy/(proton mass) ~ 500
Colliding energy ~ Few hundreds of GeV

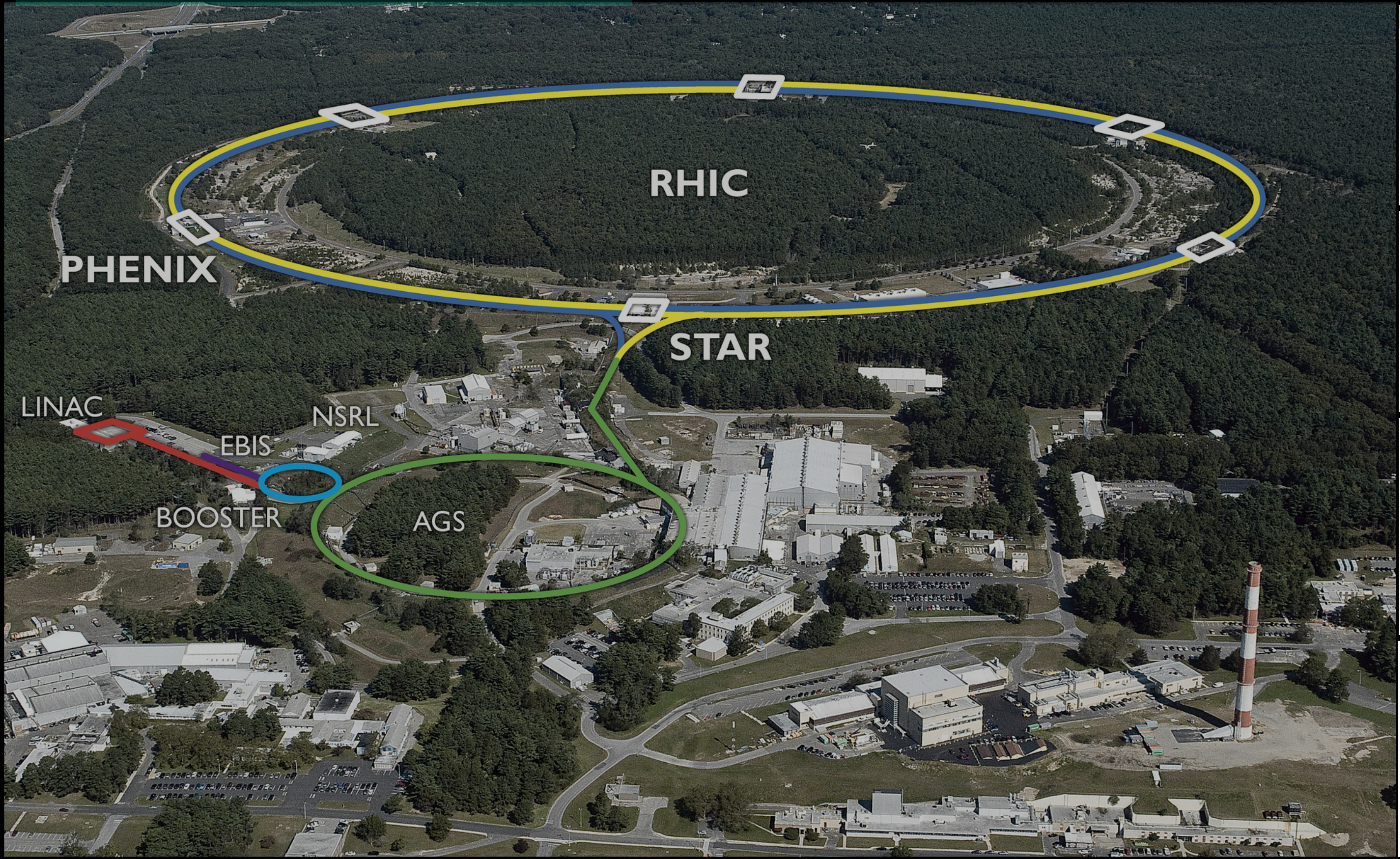
Large Hadron Collider (LHC) at CERN

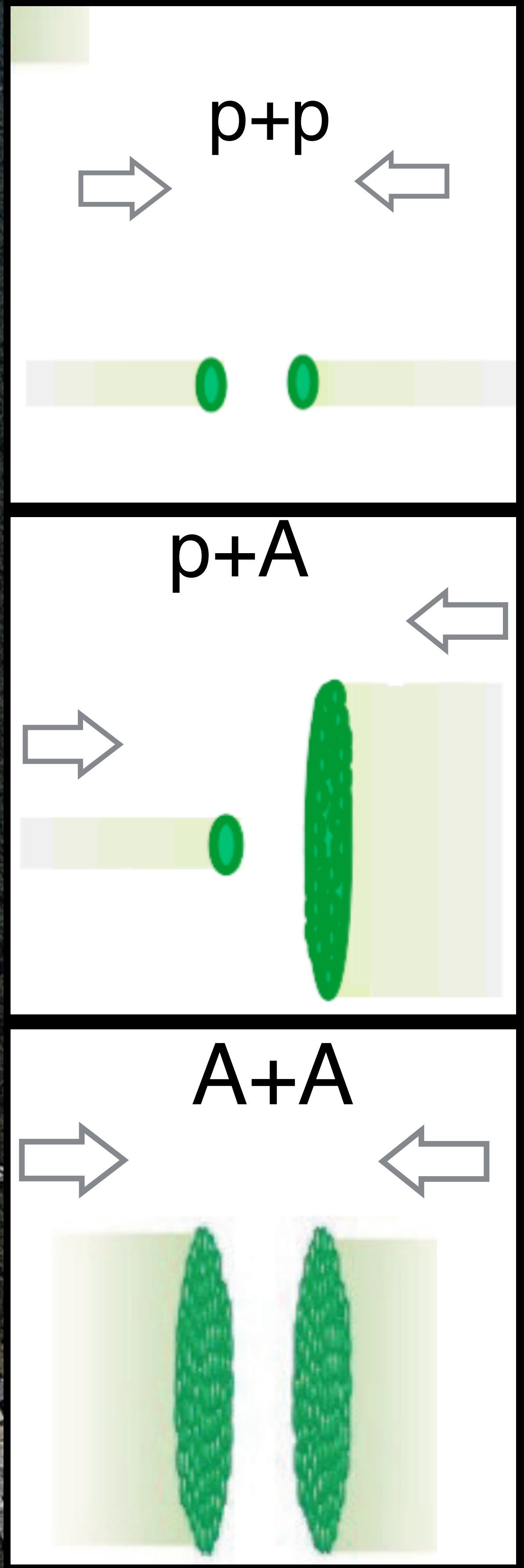


Energy/(proton mass) ~ 14000
Colliding energy ~ Few TeV

Ideal places to study QGP

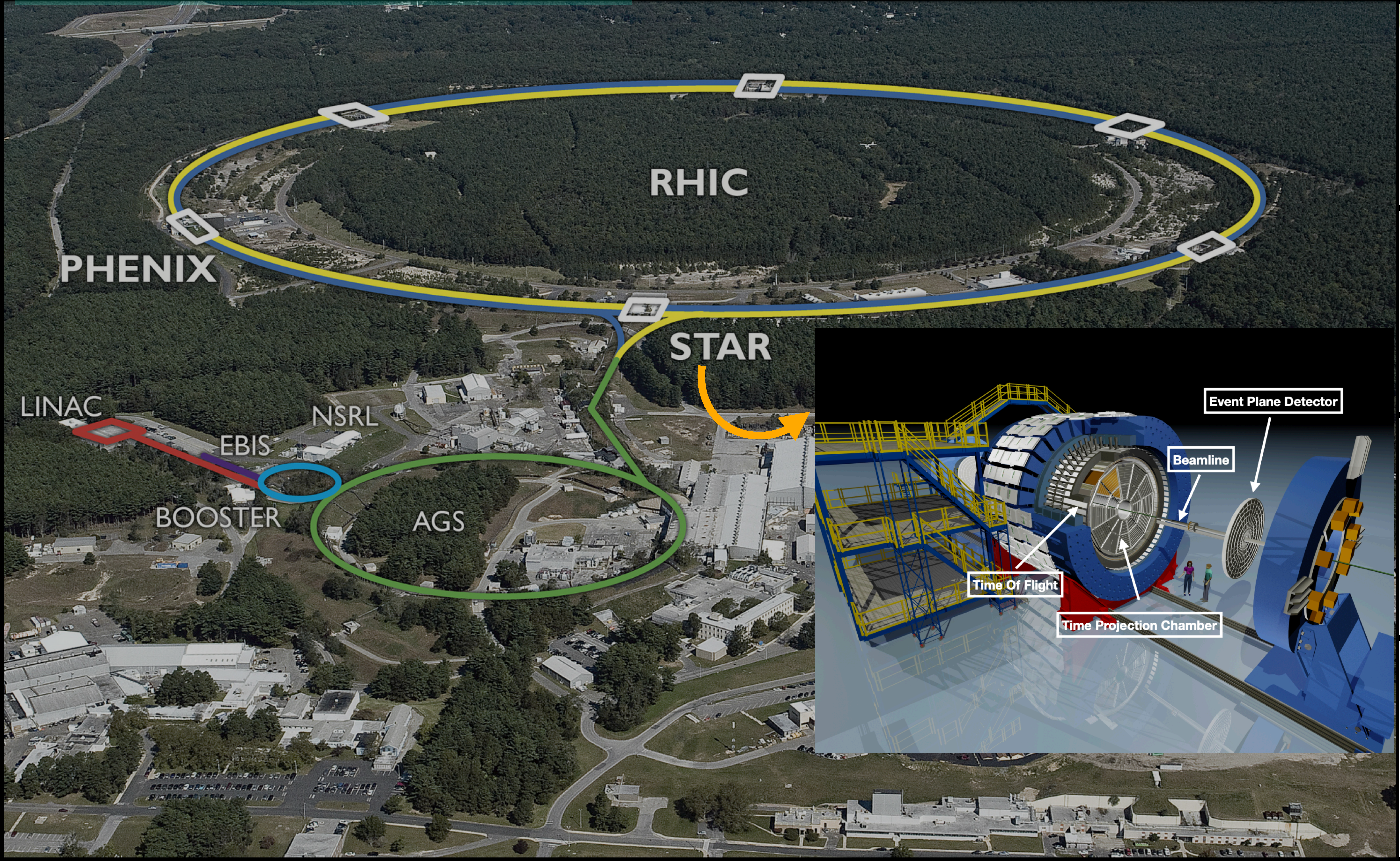
Relativistic Heavy Ion Collider (RHIC) at BNL

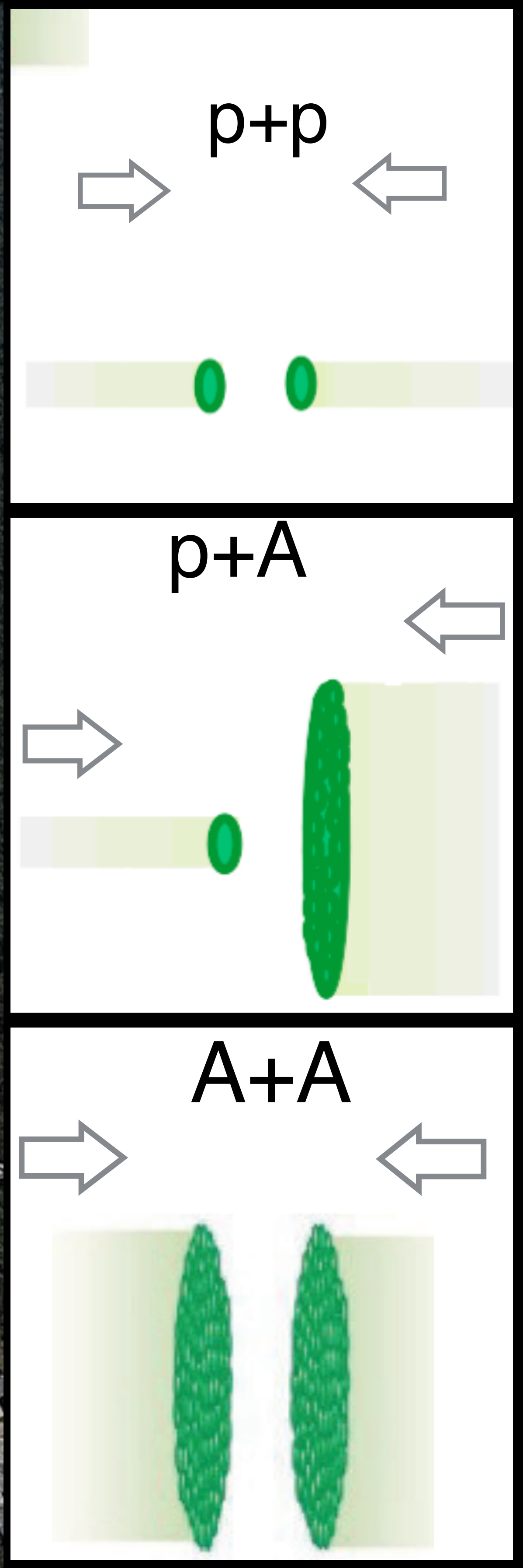




RHIC can provide collisions of p, d, ^{3}He, Al, Cu, Ru, Zr, Au, U over a wide range of energies

Relativistic Heavy Ion Collider (RHIC) at BNL

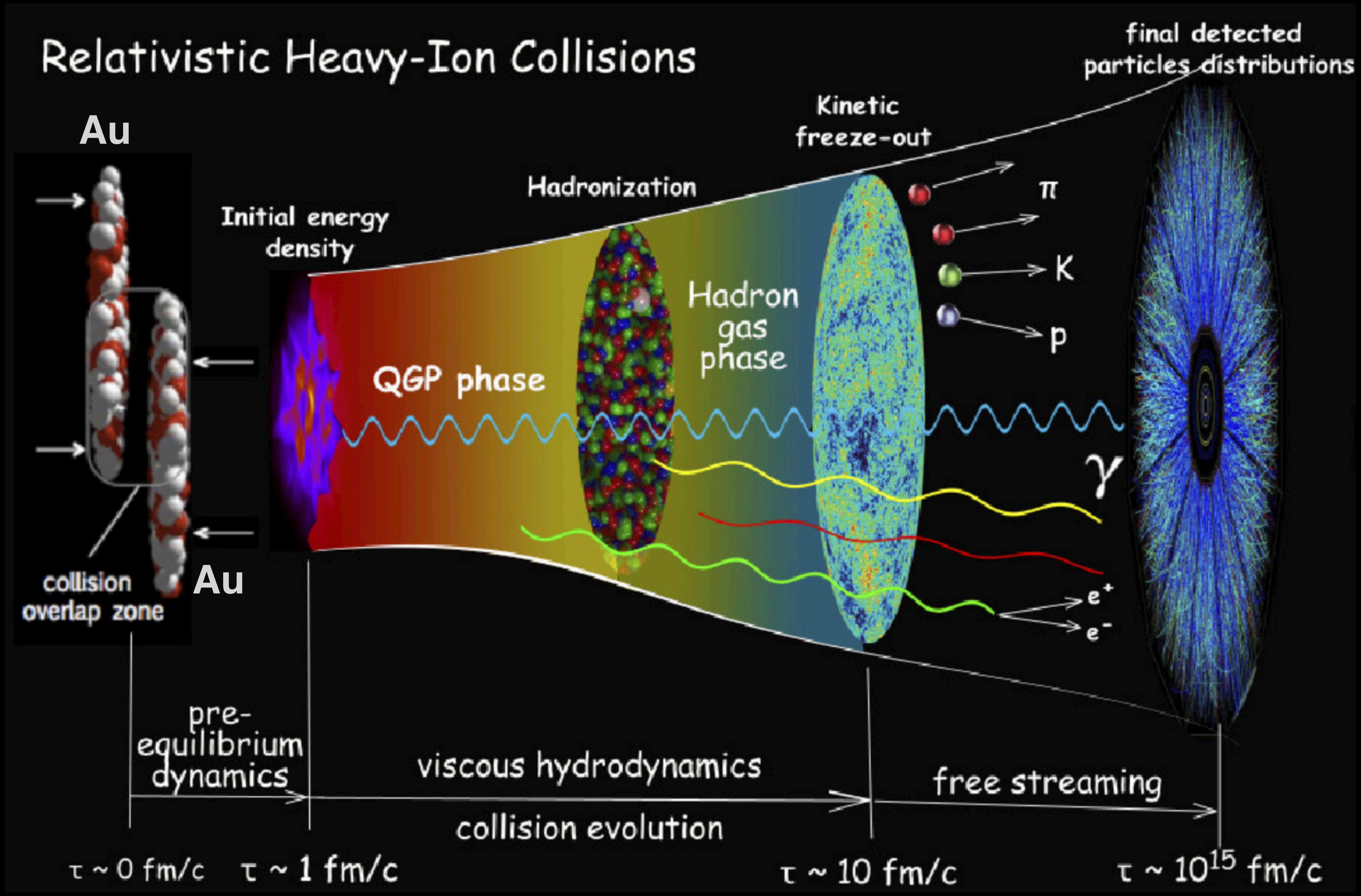




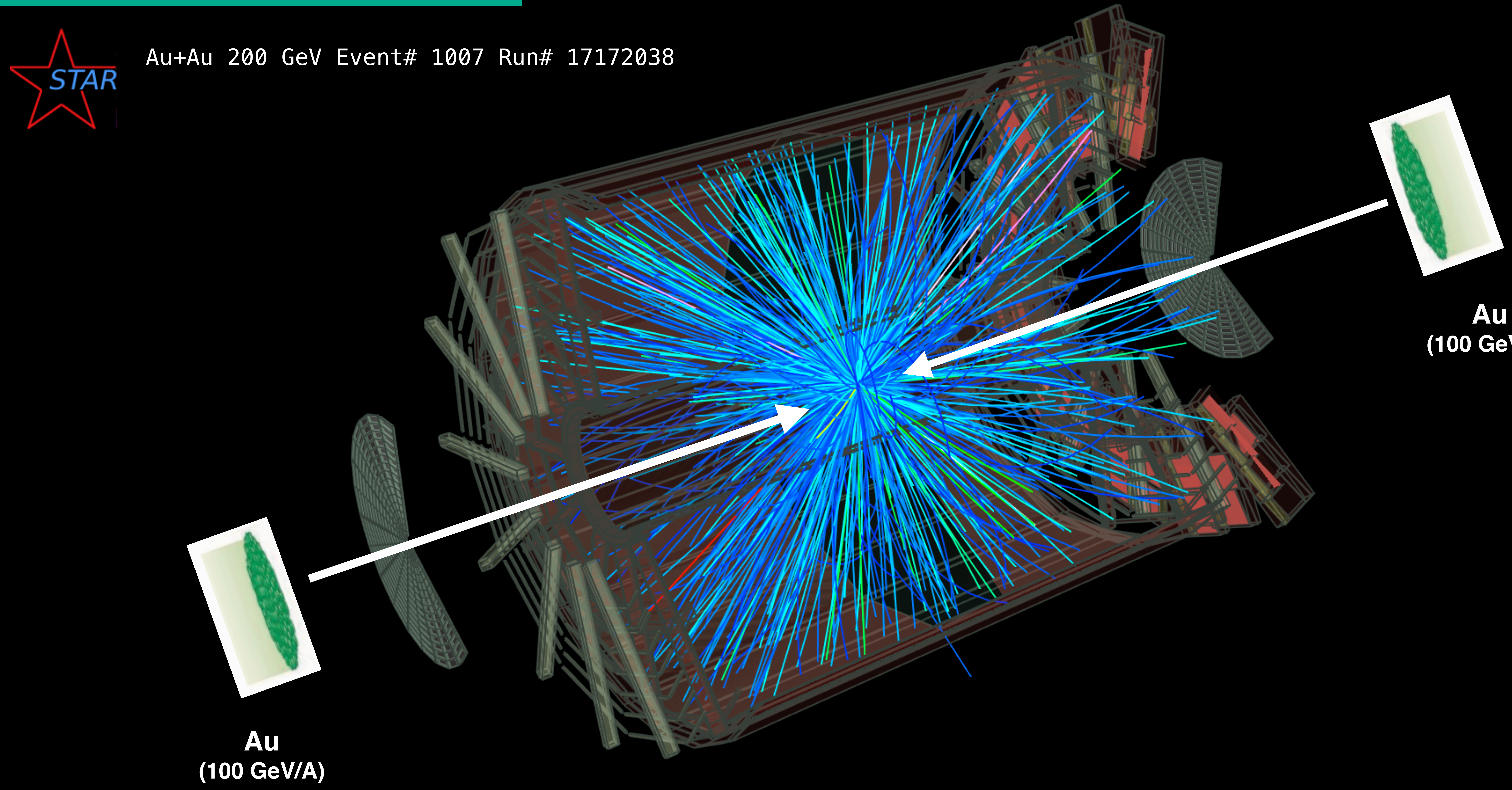
RHIC can provide collisions of p, d, ^{3}He, Al, Cu, Ru, Zr, Au, U over a wide range of energies

Heavy Ion Collisions : QGP at the Lab

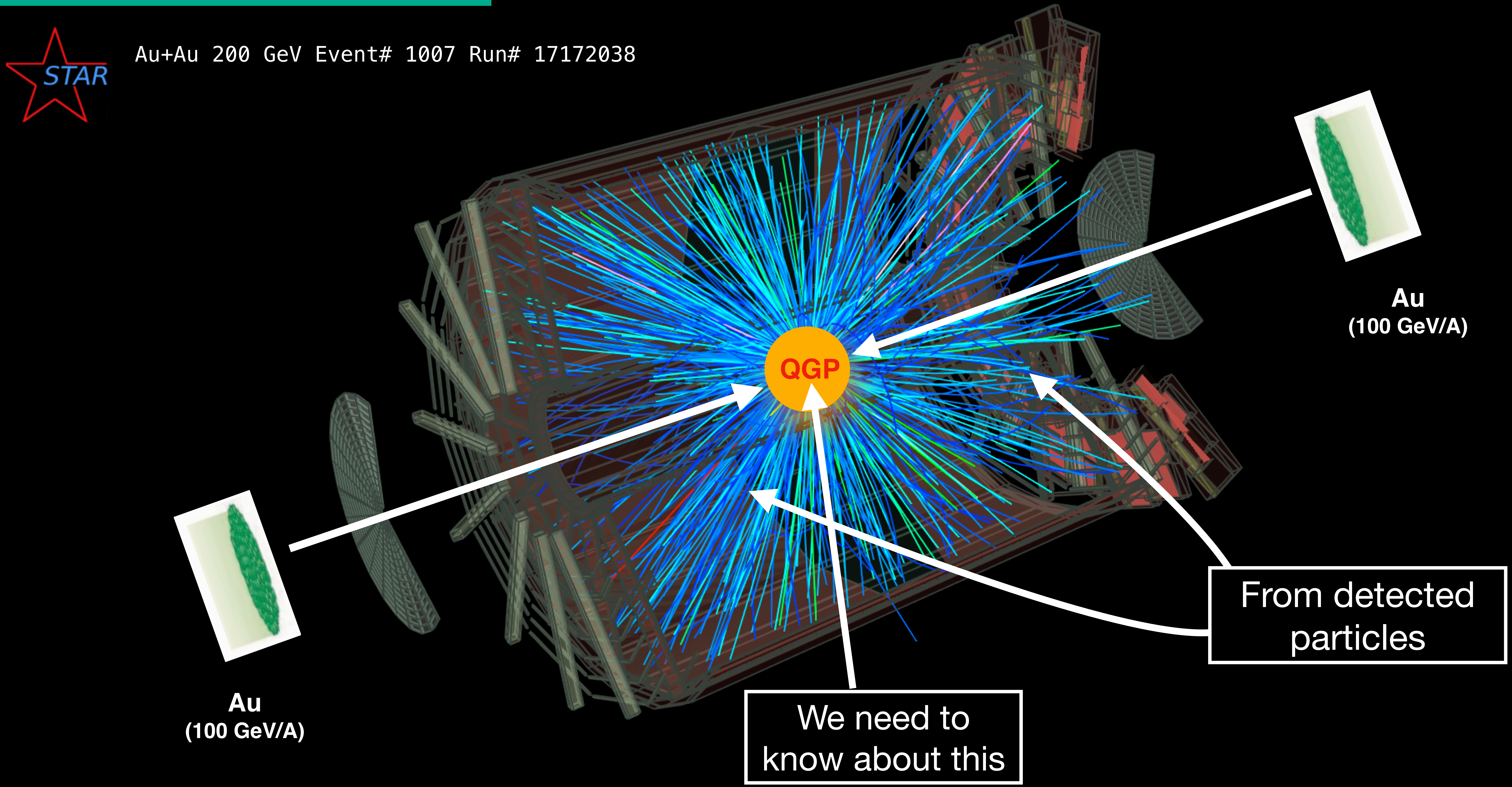
- RHIC circulates heavy nuclei (Au) almost at speed of light and smash them together
- Shortly after the collisions (~ 1 fm/c), an enormous amount of energy is released into a tiny volume
- As a result, a QGP medium possibly form
- The QGP expands and cools down rapidly, and when T falls below a critical T_c, quarks and gluons form bound states - Hadronization
- Then particles get captured in the detectors placed around collision point



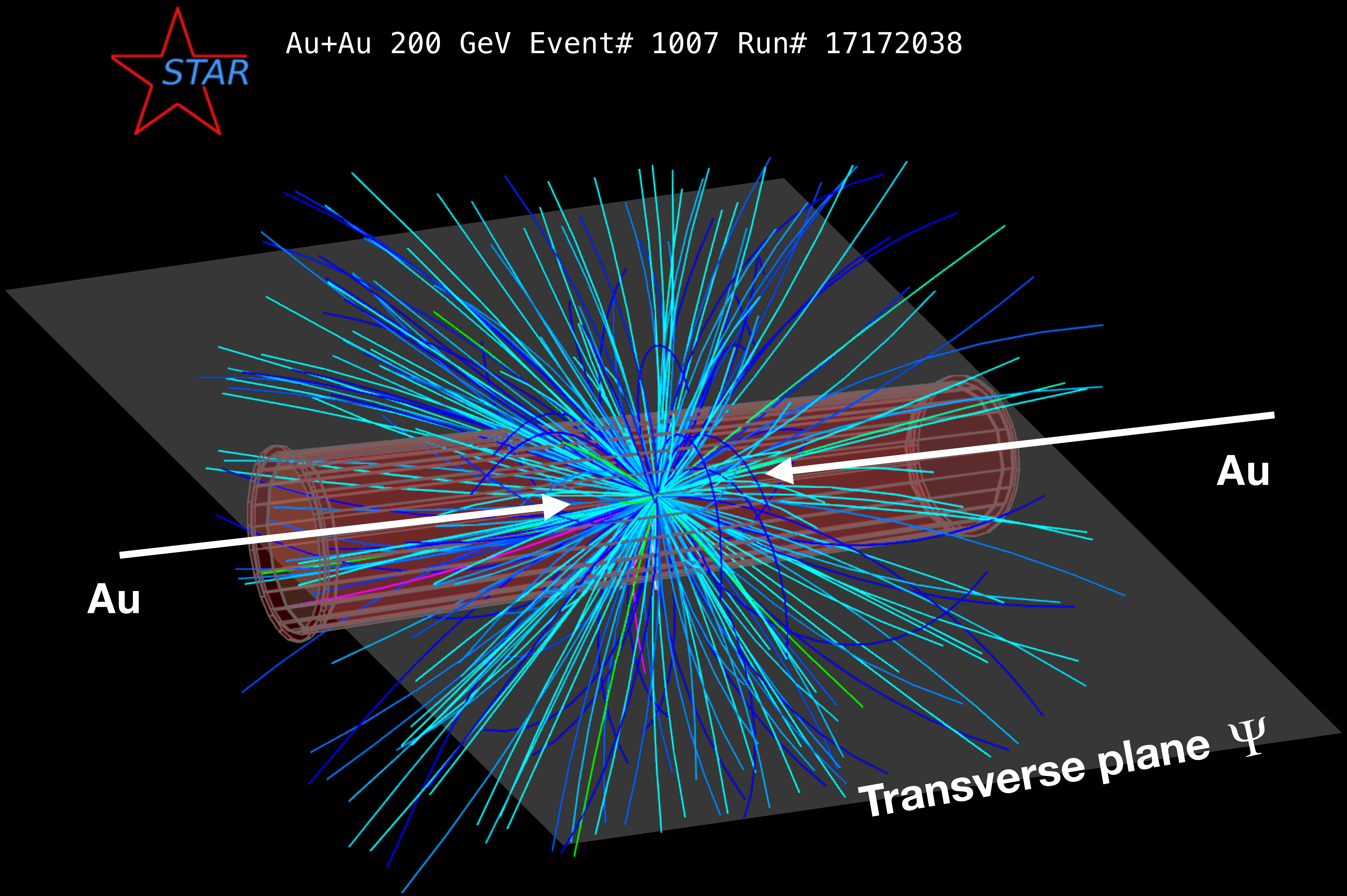
Event display of Au+Au collisions at STAR detector



What do we want to know from Au+Au collisions ?

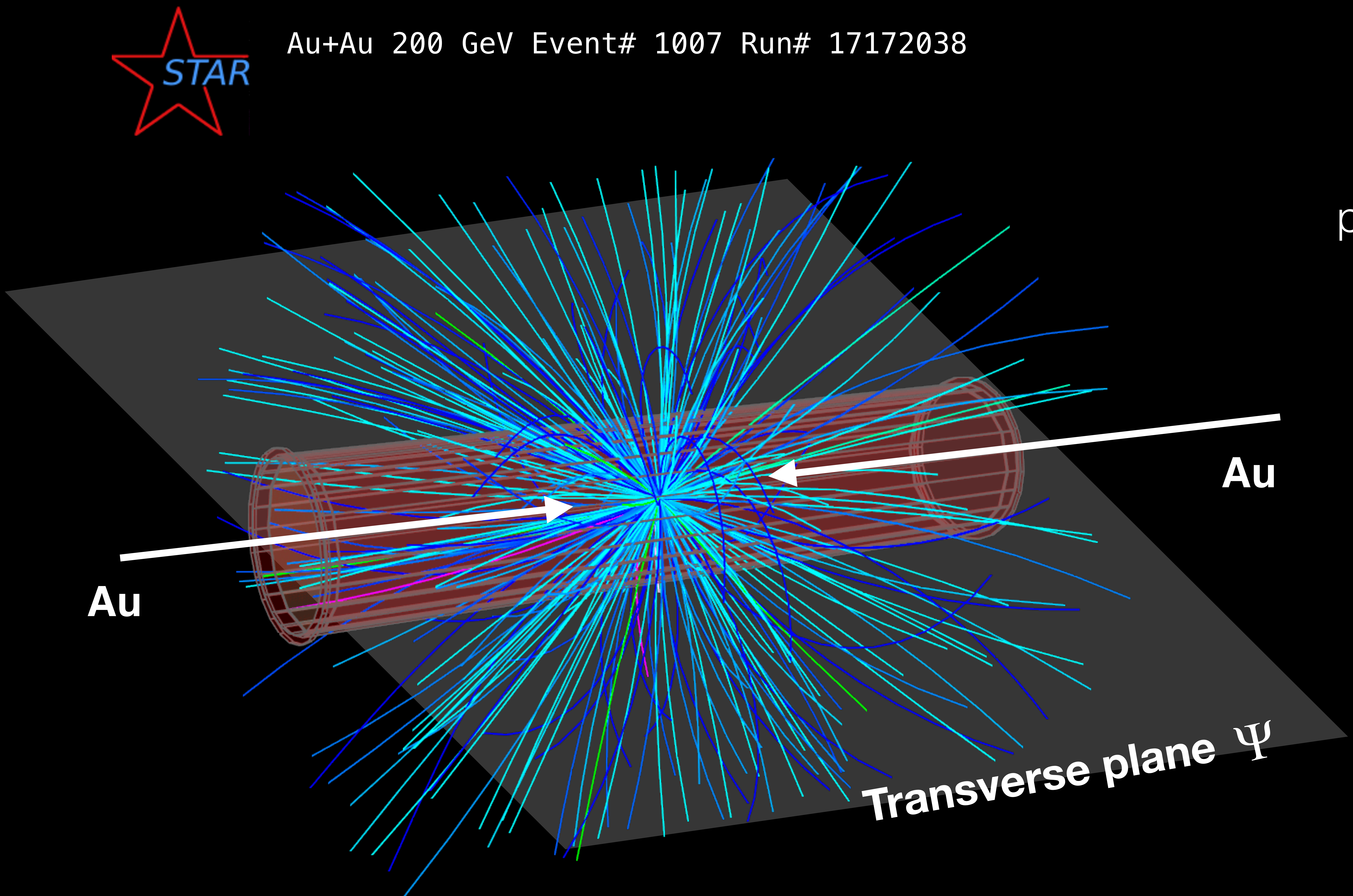


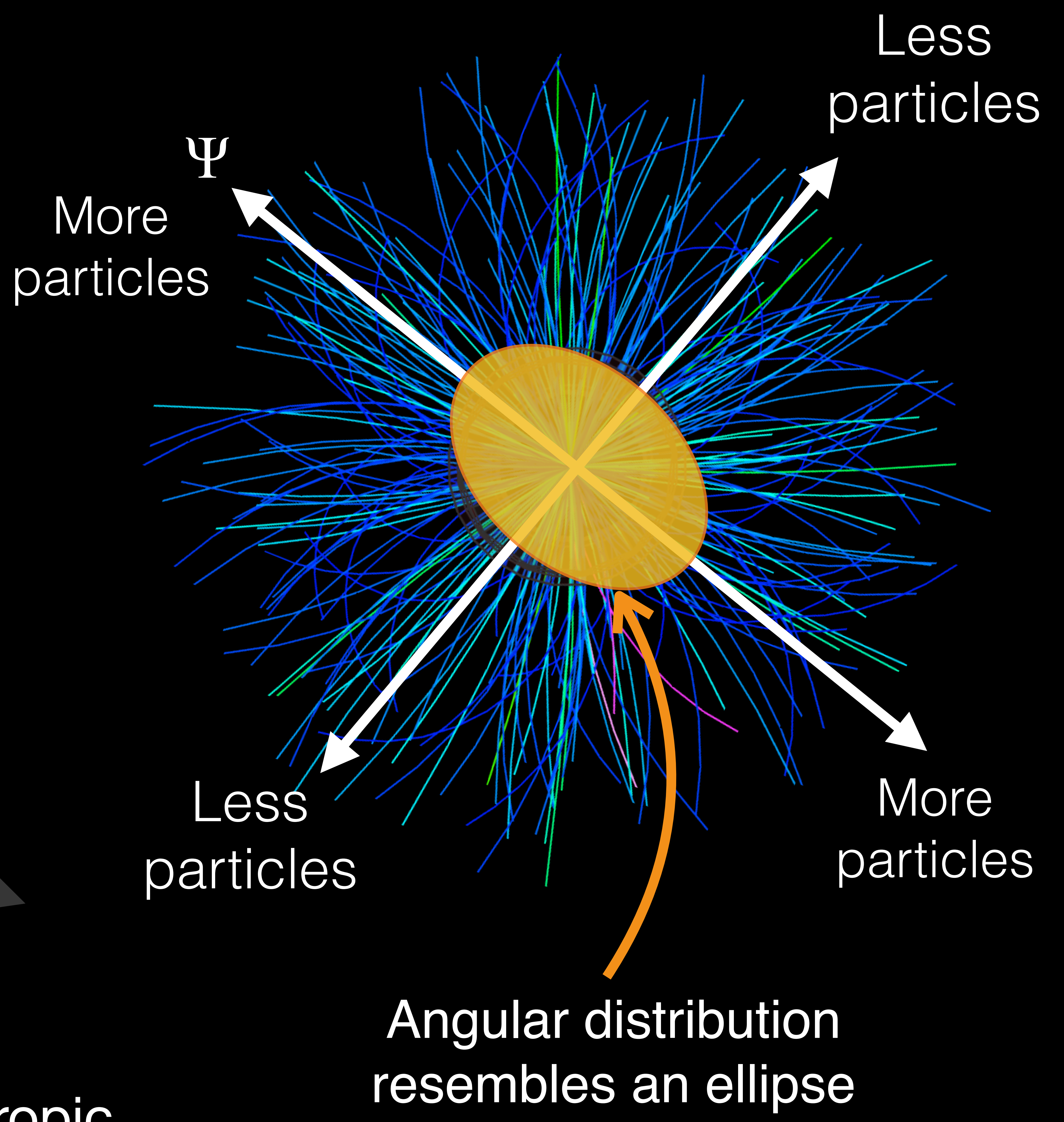
Something interesting in particle emission pattern



◉ Particle emission w.r.t transverse plane of collisions in not isotropic

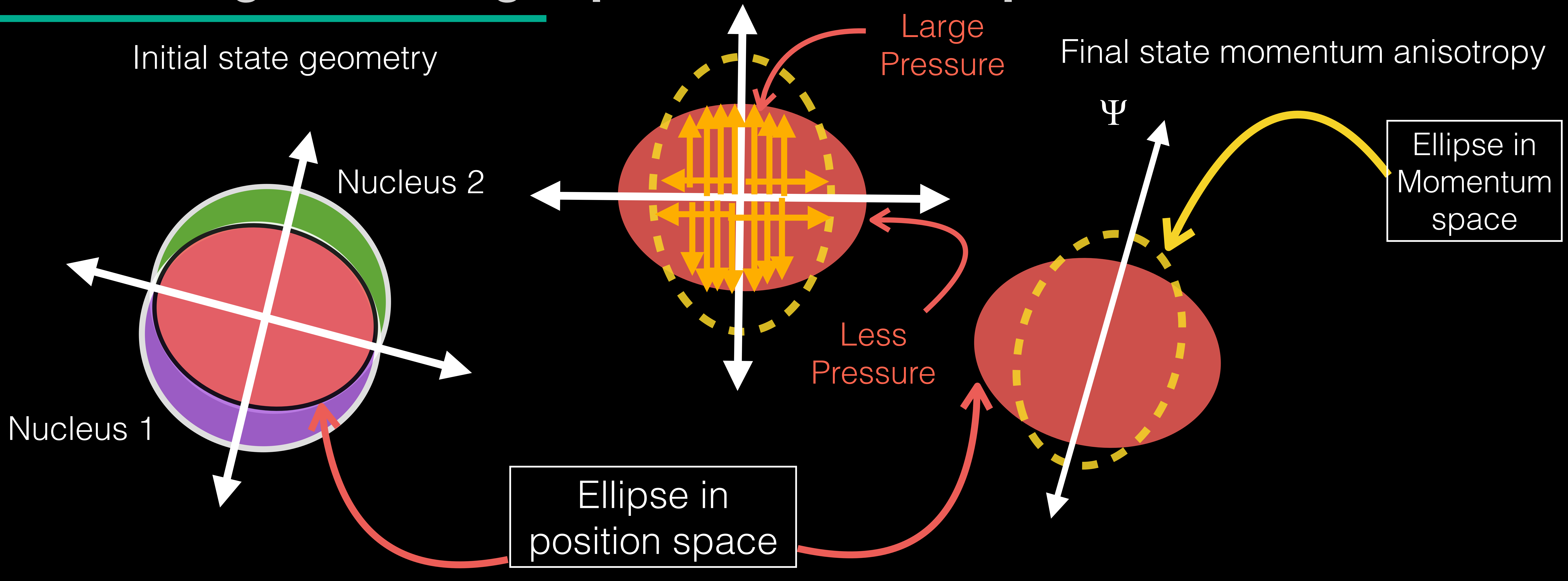
Something interesting in particle emission pattern





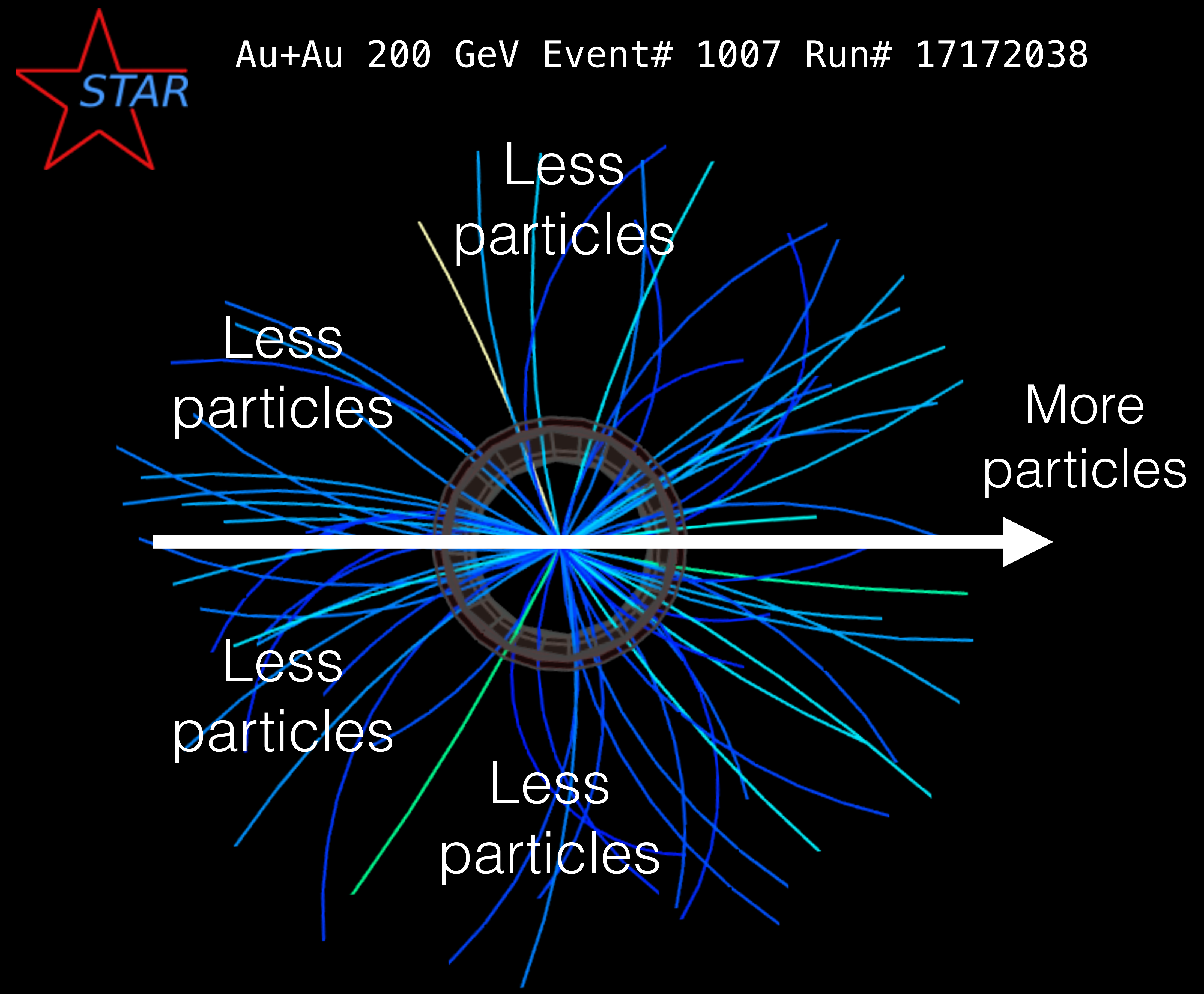
- Particle emission w.r.t transverse plane of collisions in not isotropic
- More particles along one axis and less particles in a perpendicular axis - resembles an ellipse

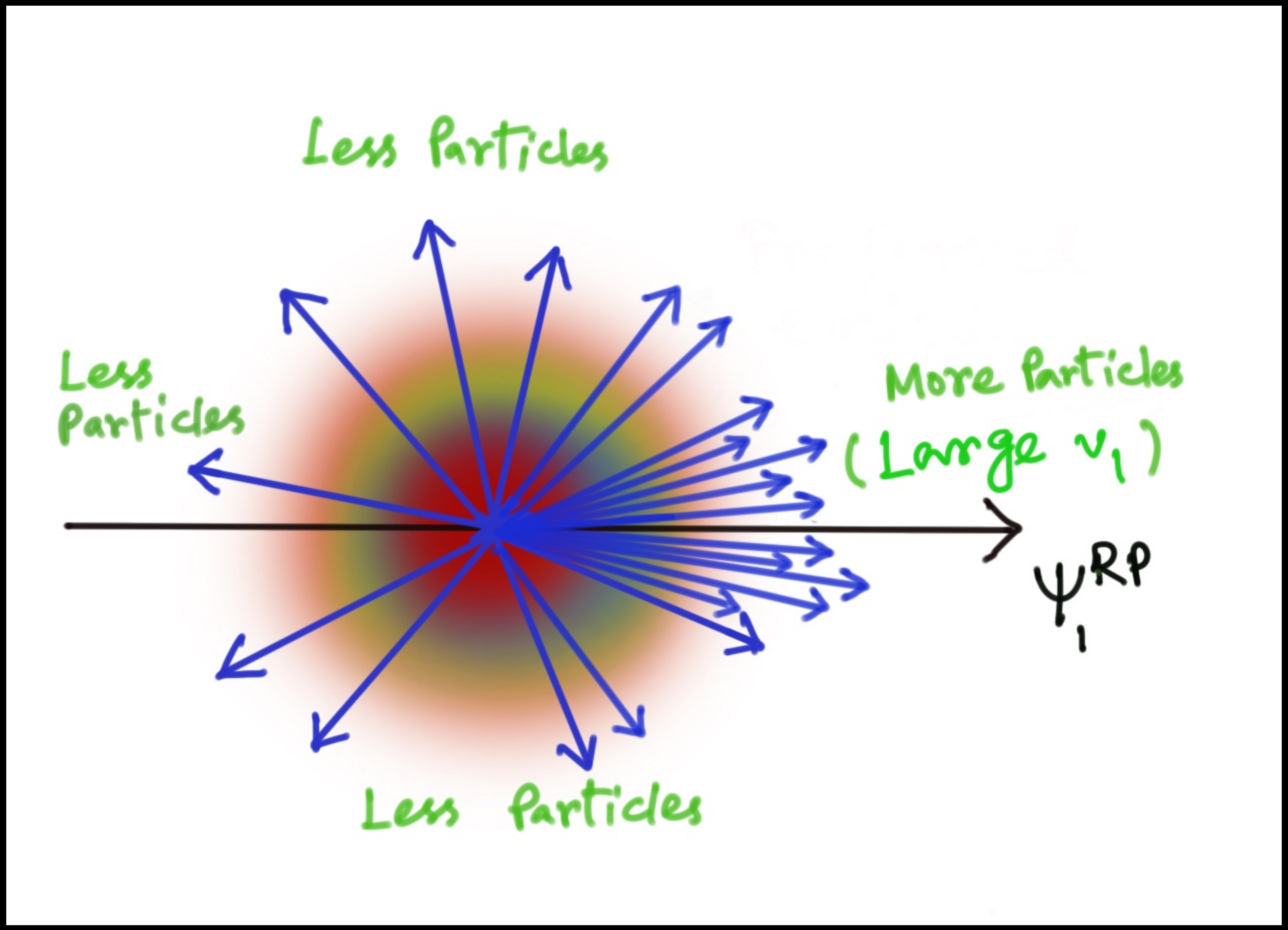
Something interesting in particle emission pattern



- Initial state collision geometry is like an almond in position space
- Large internal pressure along minor axis than major axis of the position space ellipse => momentum space ellipse
- Position space anisotropy translated into momentum space anisotropy - Elliptic flow

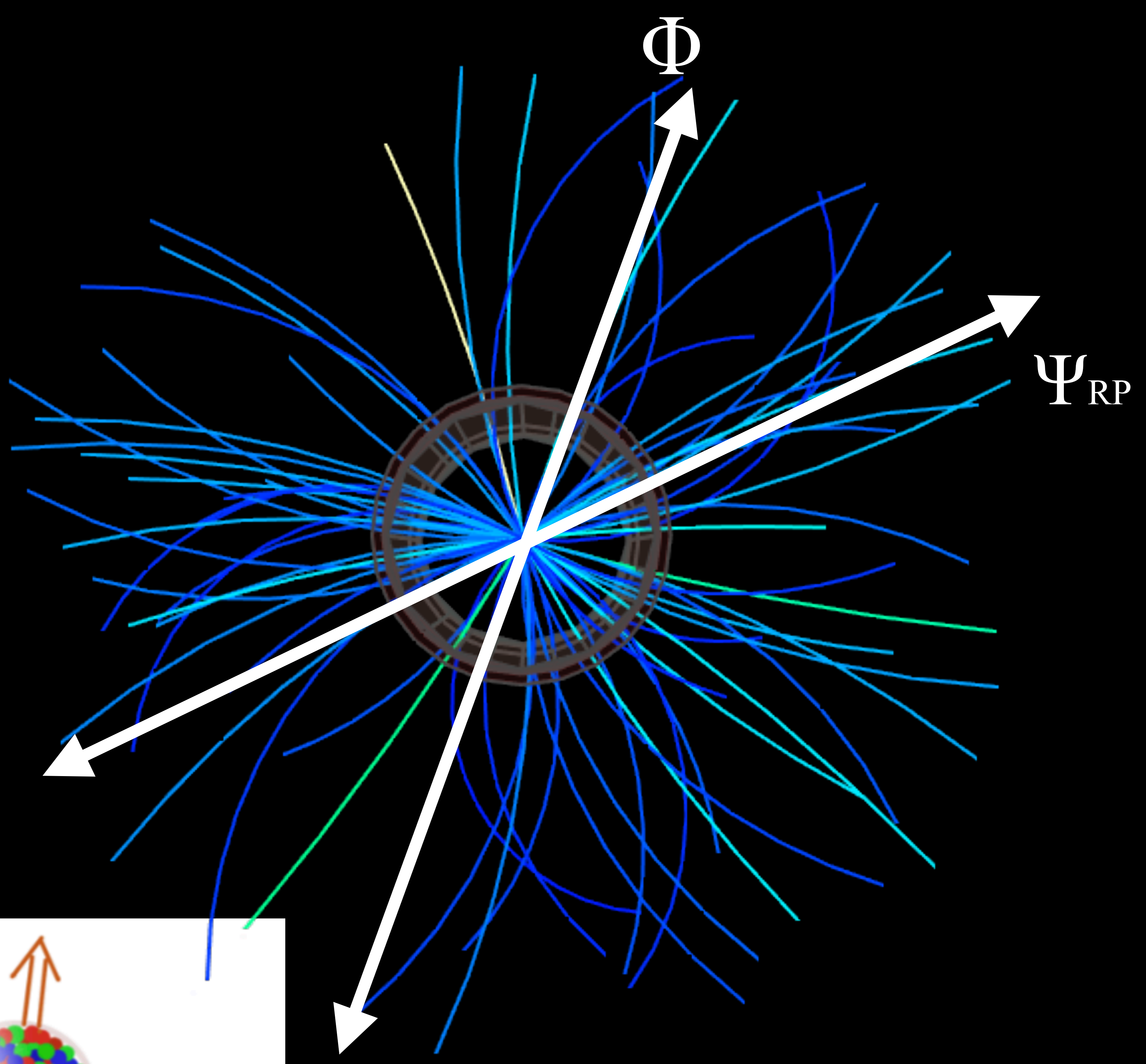
Preferred particle emission in one direction





- Particle emission might be emitted preferably in one direction
- This anisotropy describes sideward motion of the emitted particles - One directional => Directed flow

Characterization of anisotropic flow (v_n)

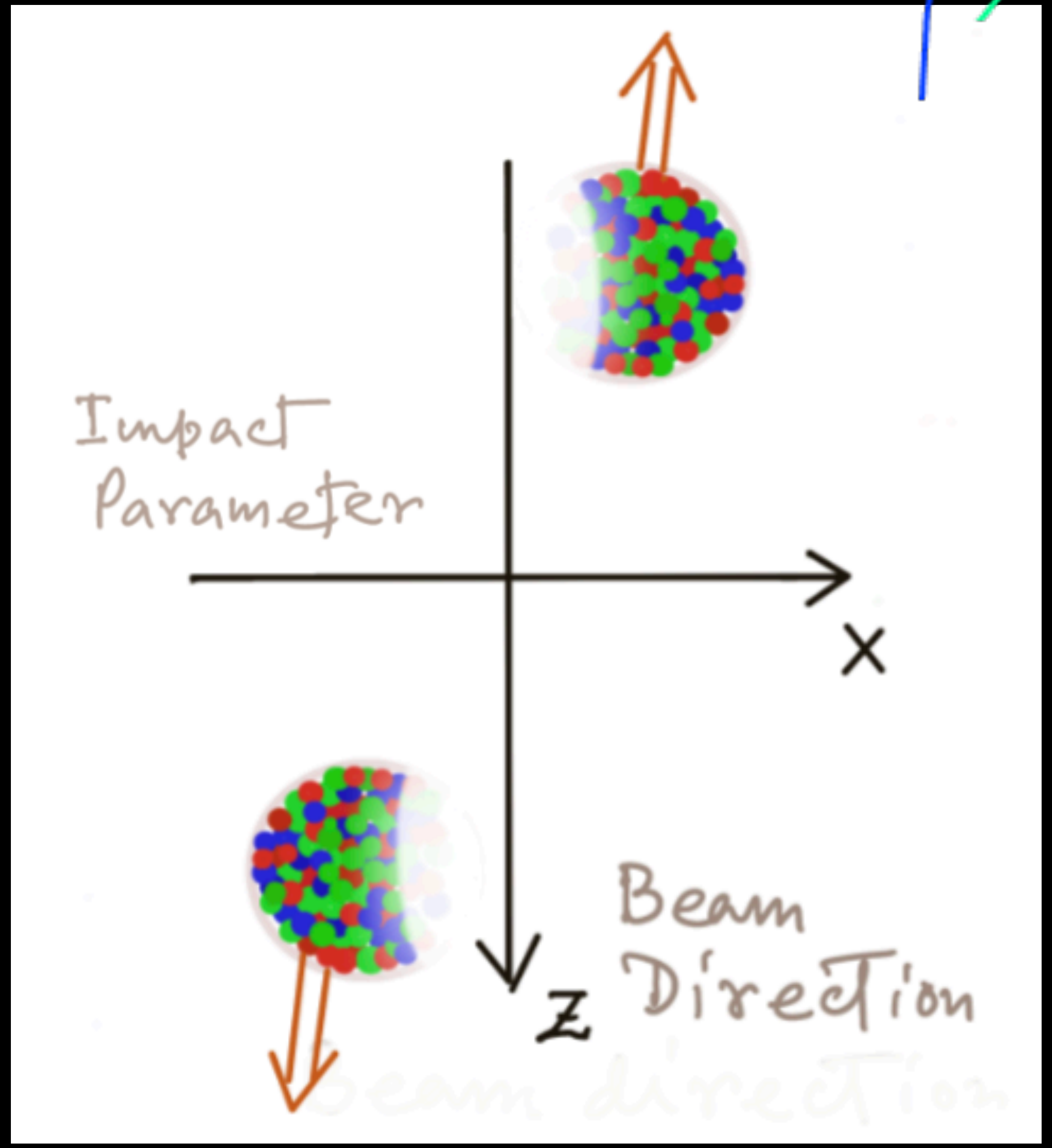


- Angular distribution is characterized by Fourier series
- Express particle angular distributions in Fourier series,

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2\sum_{n=1}^{+\infty} v_n \cos n(\phi - \Psi_{RP})\right)$$

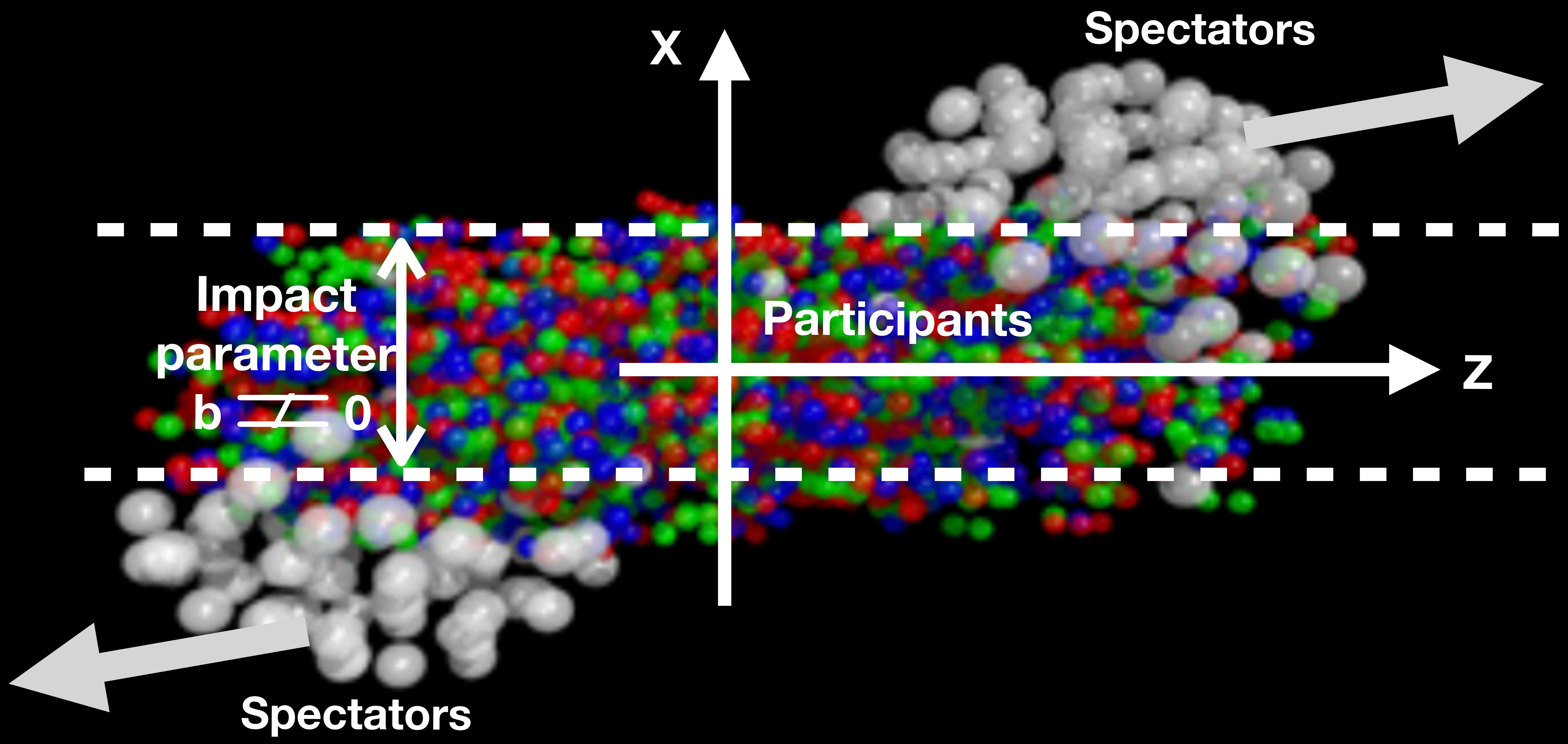
where $v_n = \langle \cos n(\phi - \Psi_{RP})\rangle$

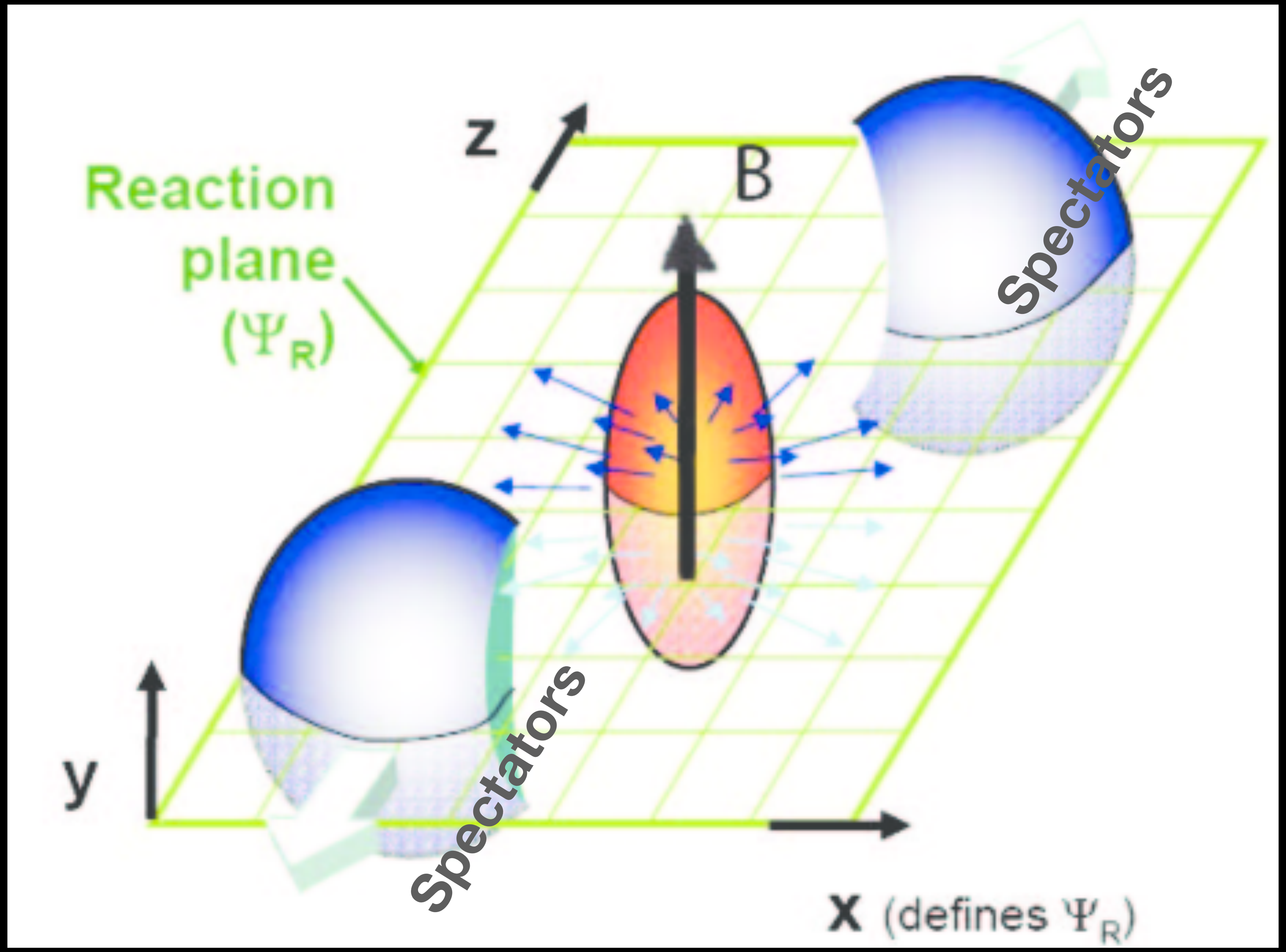
Ψ_{RP} ⟶ Reaction Plane angle   XZ -> Reaction Plane (RP)

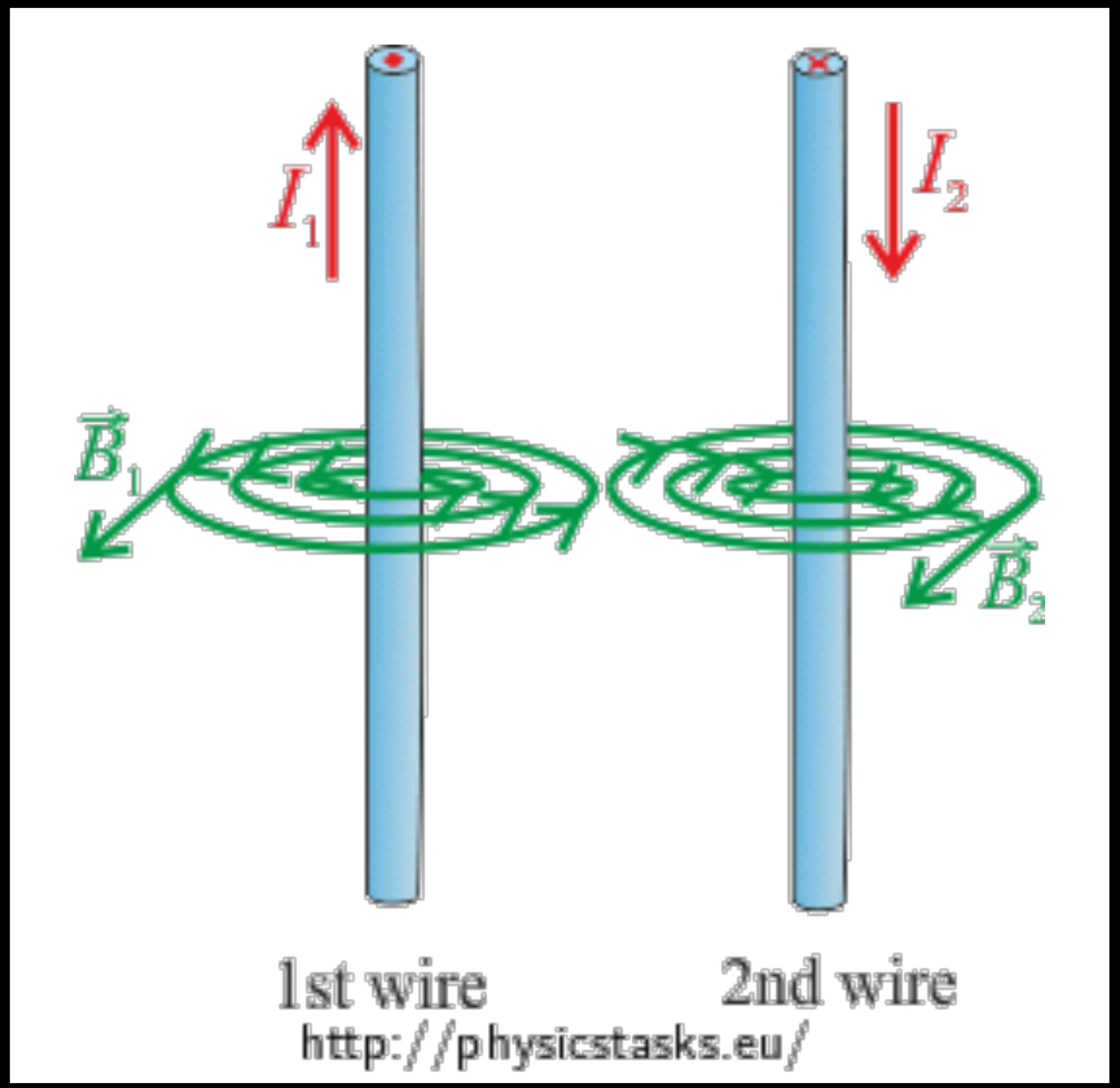


- v_n ⟶ flow harmonics
- v_1 ⟶ directed flow, v_2 ⟶ elliptic flow, v_3 ⟶ triangular flow, and so on …

What if there is non central collisions?







- Non-central HICs (Non-zero impact parameter)
- Charged spectator nuclei produce electric currents (like two parallel current carrying wires in opposite directions
- The currents can produce magnetic fields
- Magnetic fields due to these two sources add up

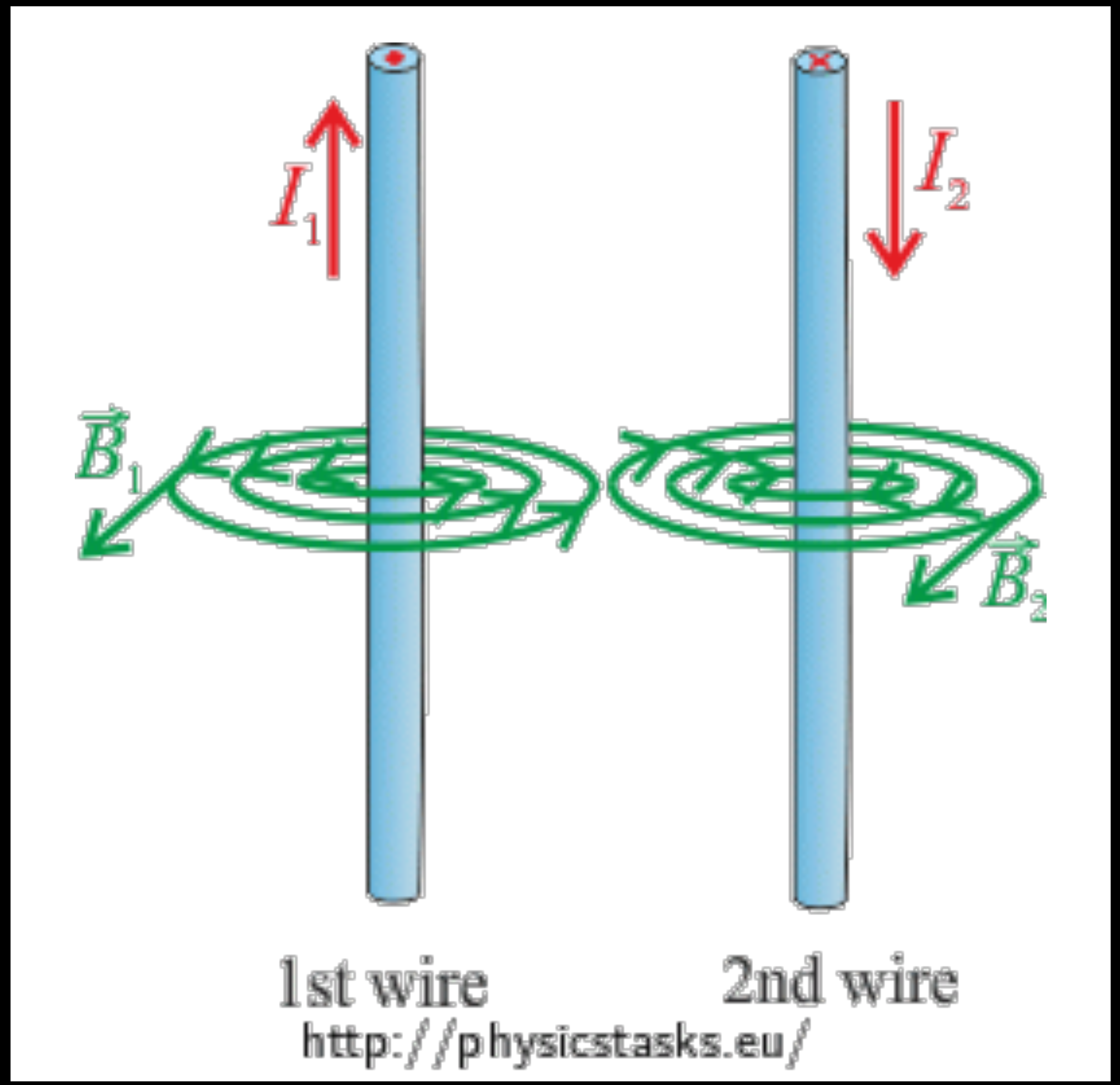
Estimates of the produced magnetic field

- A crude estimate of the magnetic field (using Biot-Savart Law):

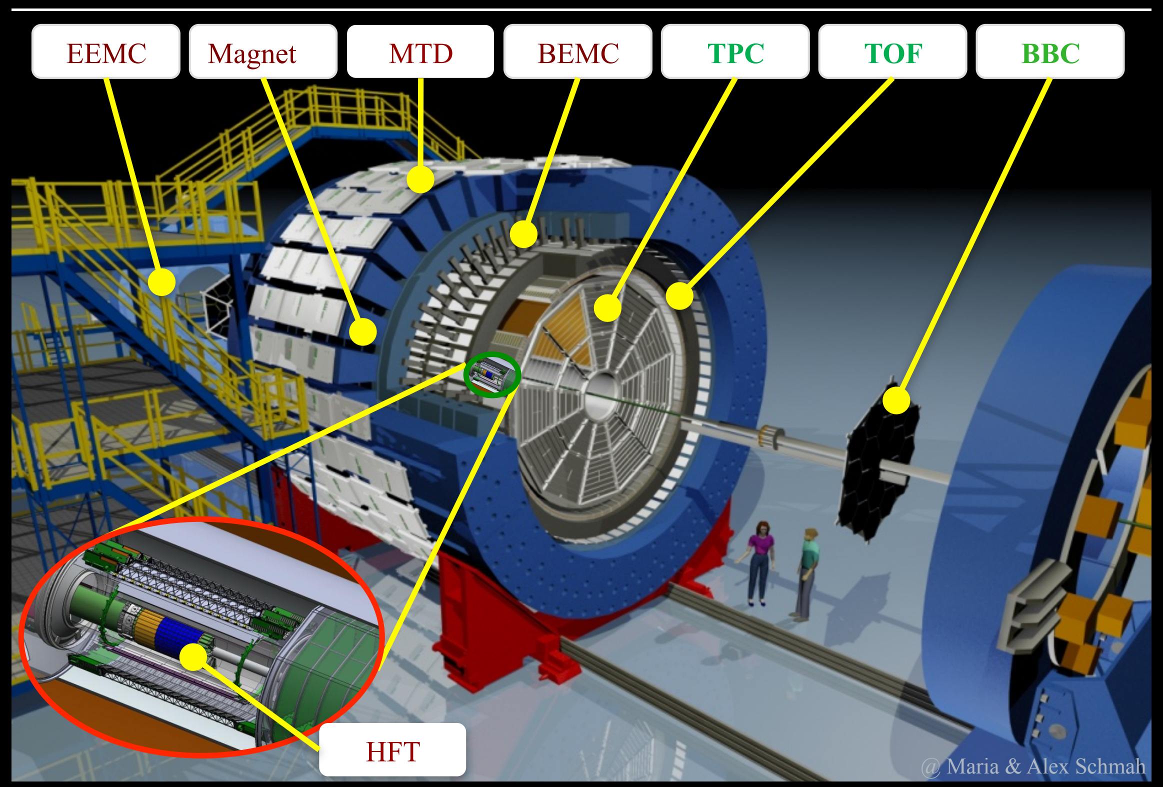
$-eB_y \sim 40m_\pi^2 \sim 10^{18}$Gauss (At RHIC Au+Au collisions, $\sqrt{s_{NN}} = 200$ GeV, b = 5 fm, t = 0)

- Strongest magnetic field ever produced in the universe

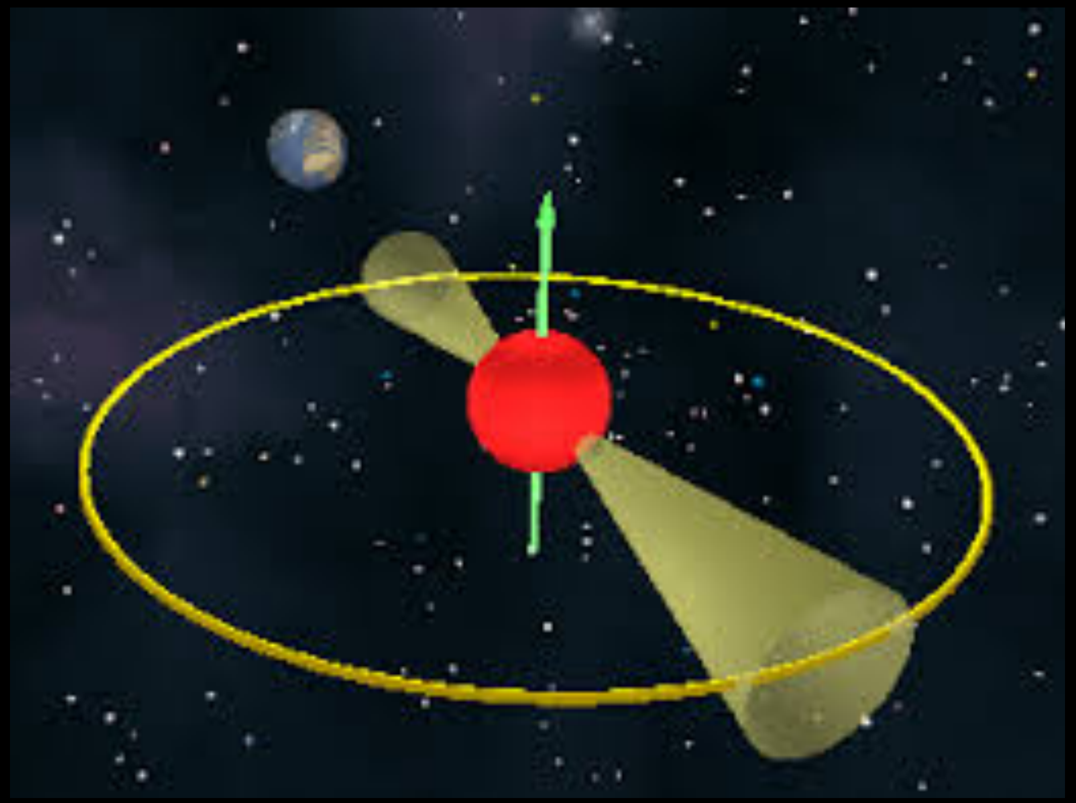
- Field has observable effects on properties of produced particles, such as anisotropic flow



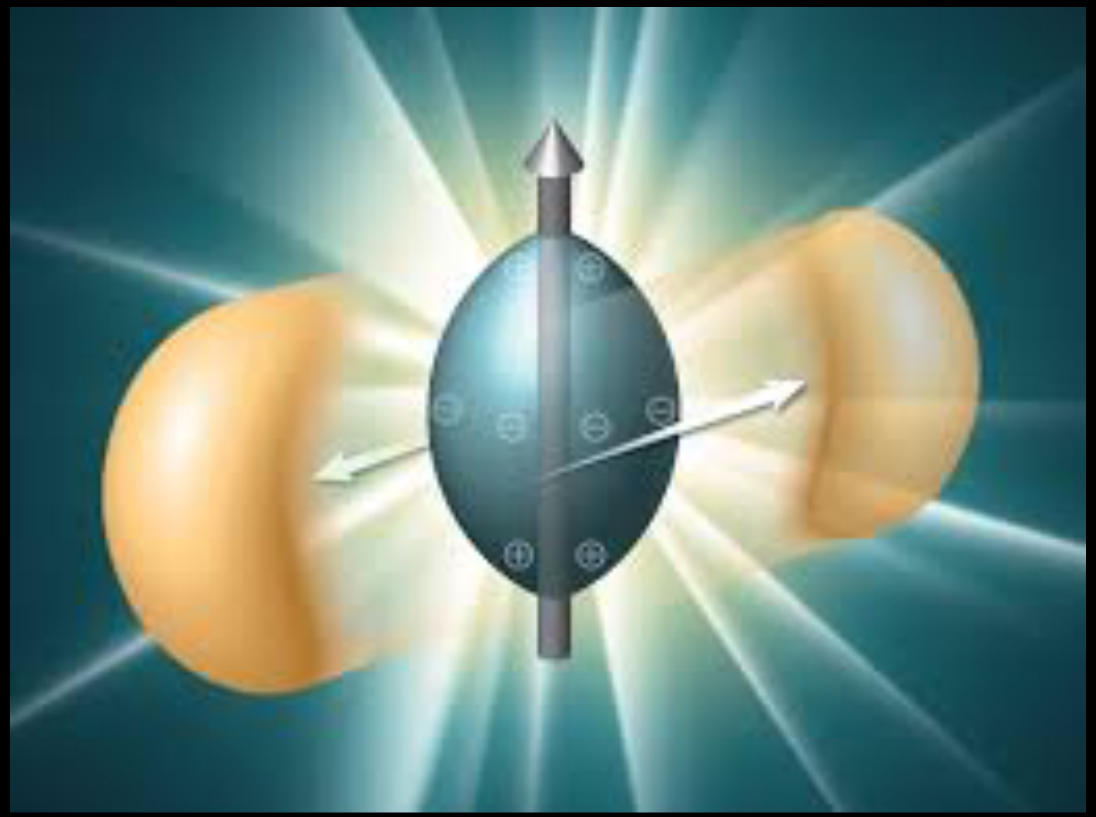
Earth
~0.5 Gauss



STAR magnet
~5000 Gauss



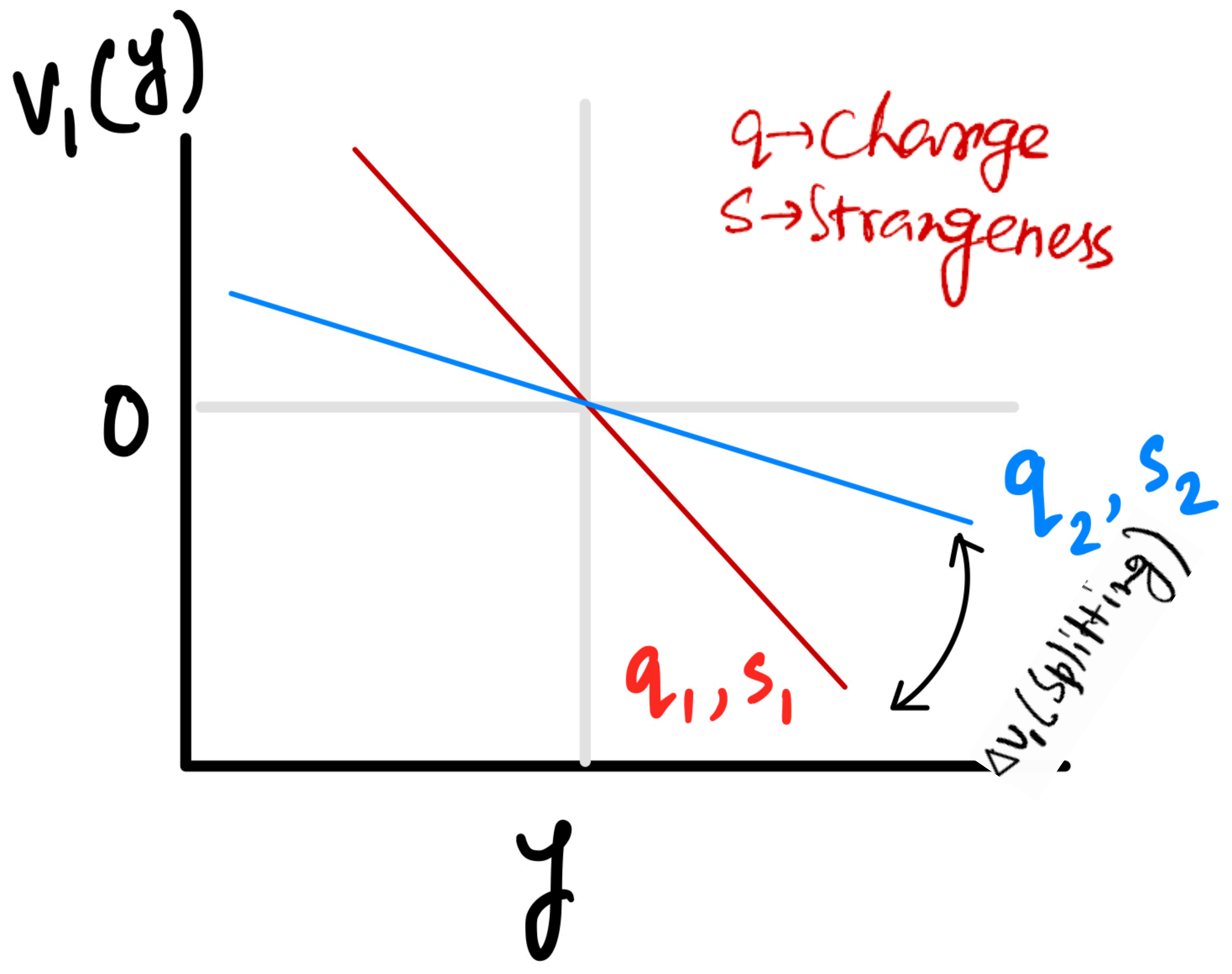
Neutron Star (Magentar)
~ 10^{14} Gauss

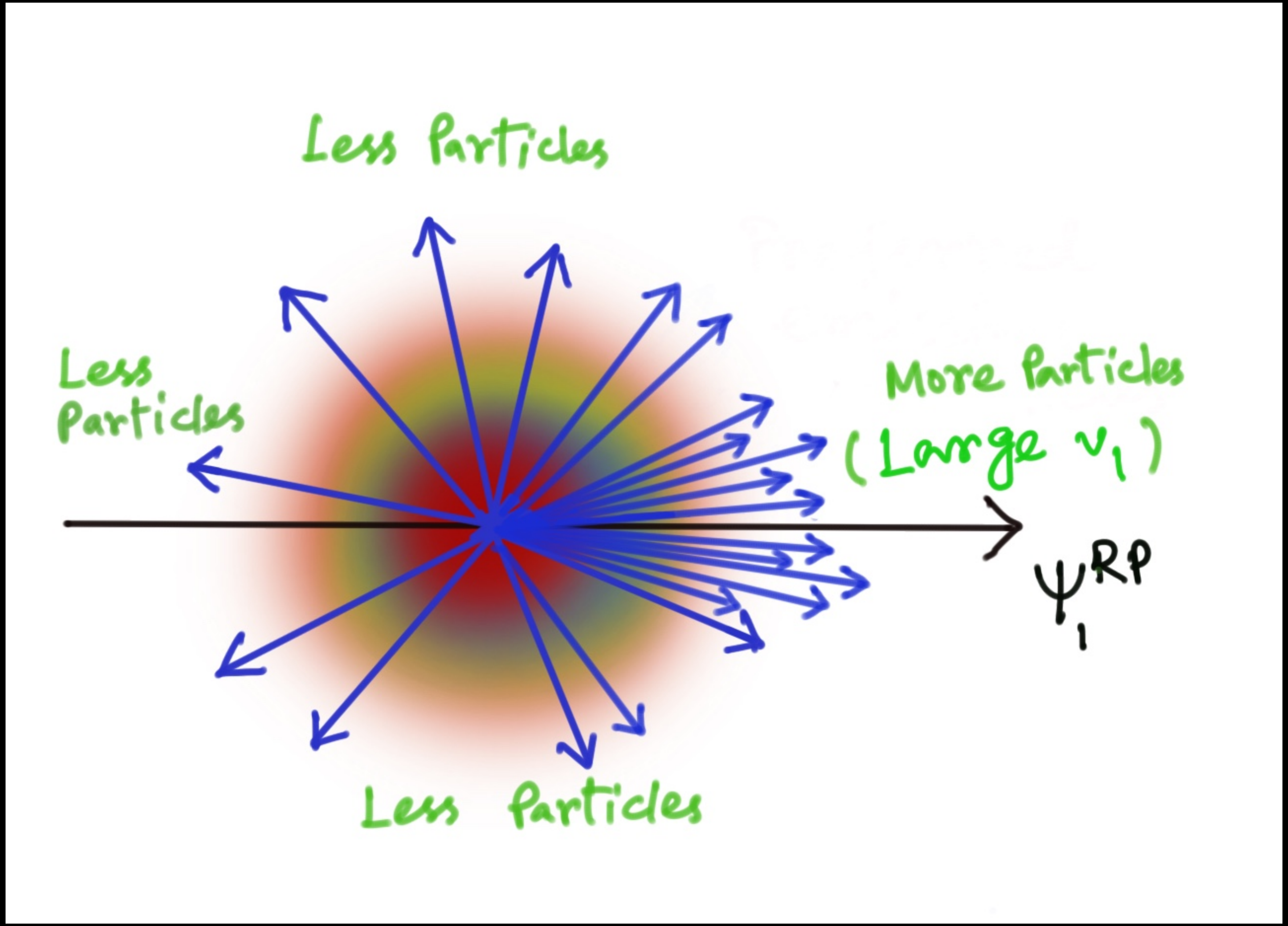


Heavy ion collisions
~ 10^{18} Gauss

Directed flow (v_1) and splitting (Δv_1)

- Directed flow (v_1) describes sideward motion of particles and can be measured with particle rapidity

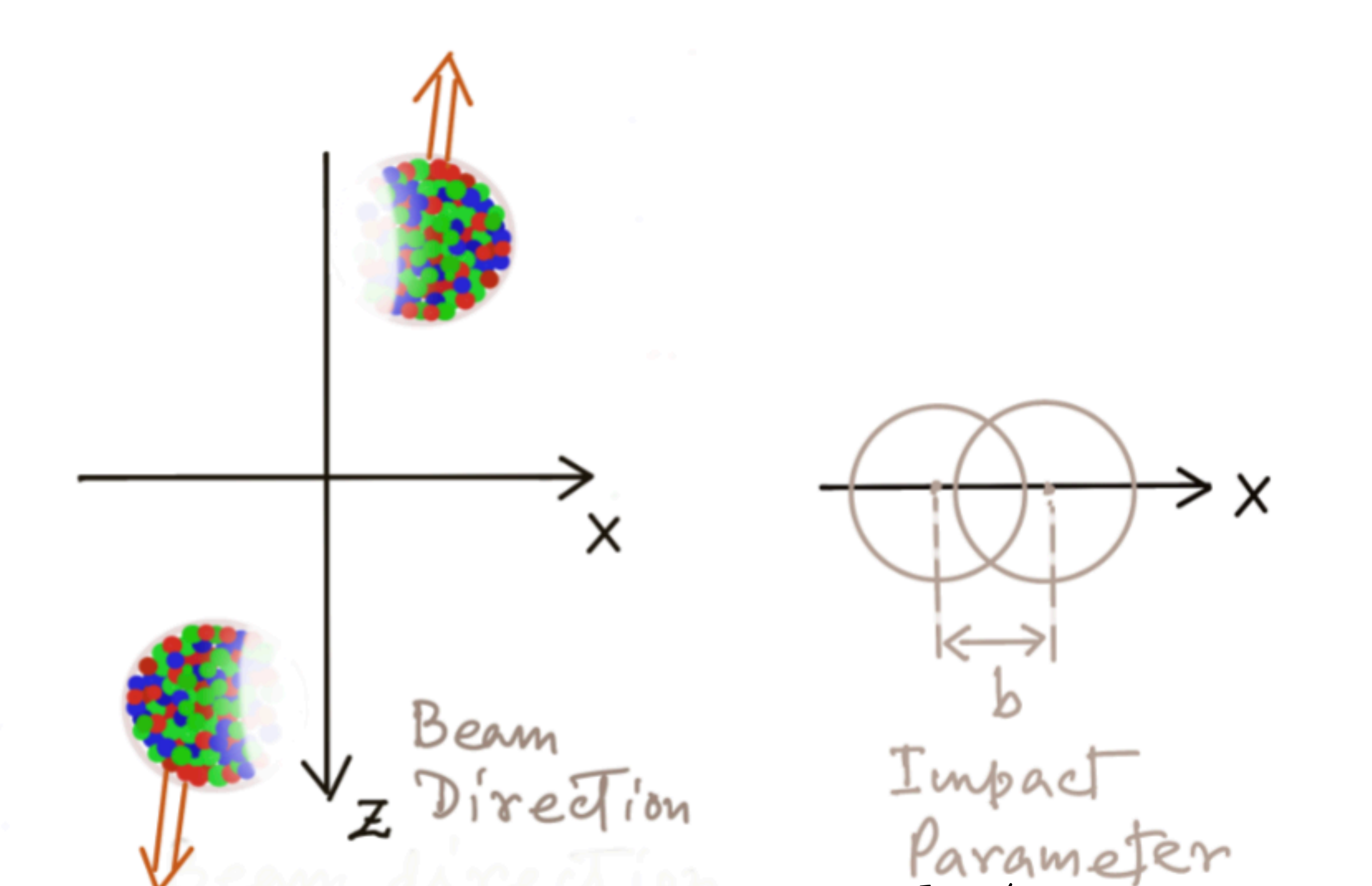




- Splitting: $\Delta v_1 = v_1\,(q1, S1) - v_1\,(q2, s2)$

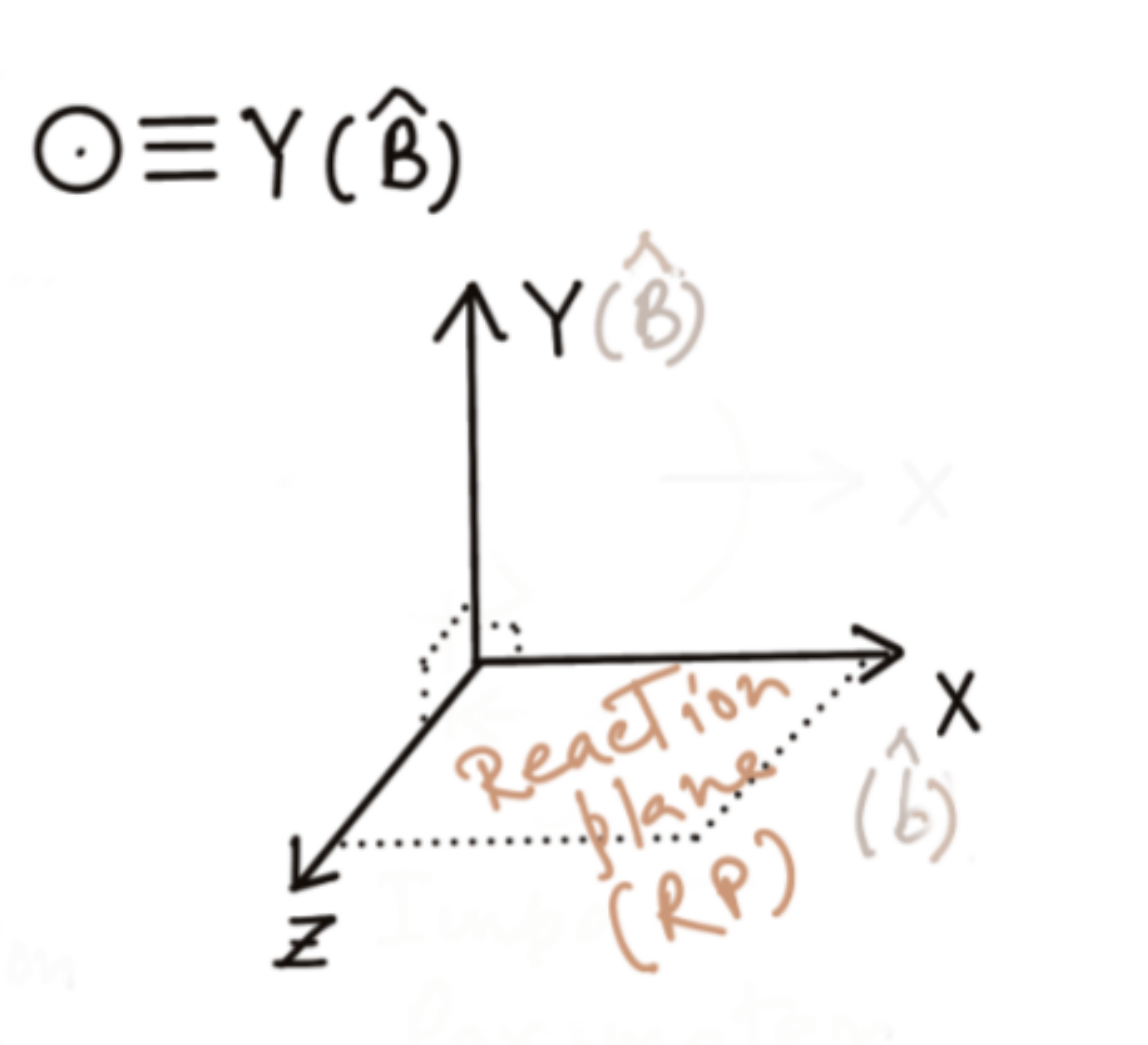
- EM field can have observable consequences on v_1 splitting between charged particles

EM field drives splitting

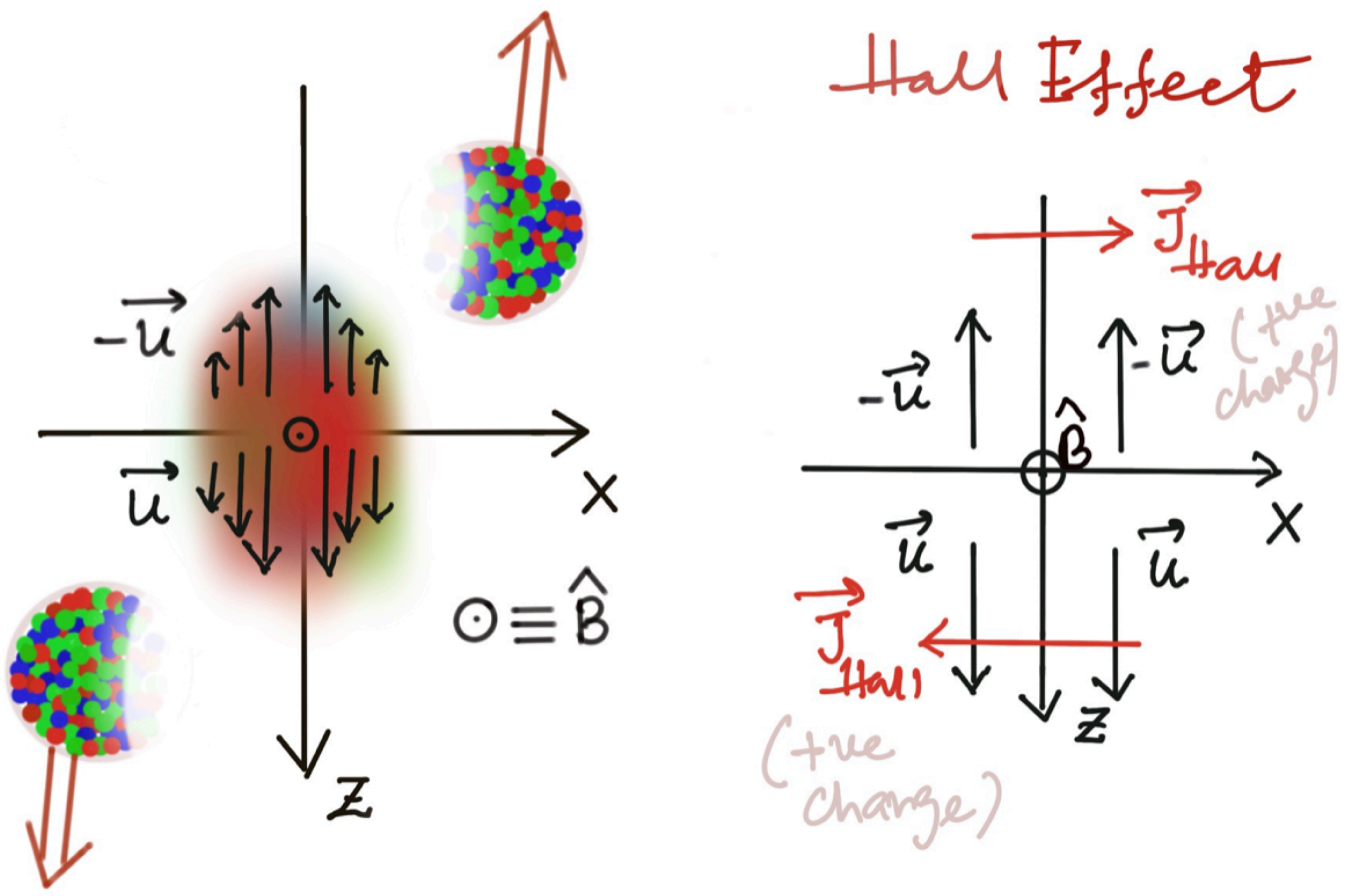


$b \neq 0$

- Assume a non-central HIC $(b \neq 0)$
- Beam direction: $\hat{\text{z}}$, Impact parameter: $\hat{\text{x}}$
- Reaction plane (RP): xz
- Charged spectators produce magnetic field - $\vec{B} \perp RP$



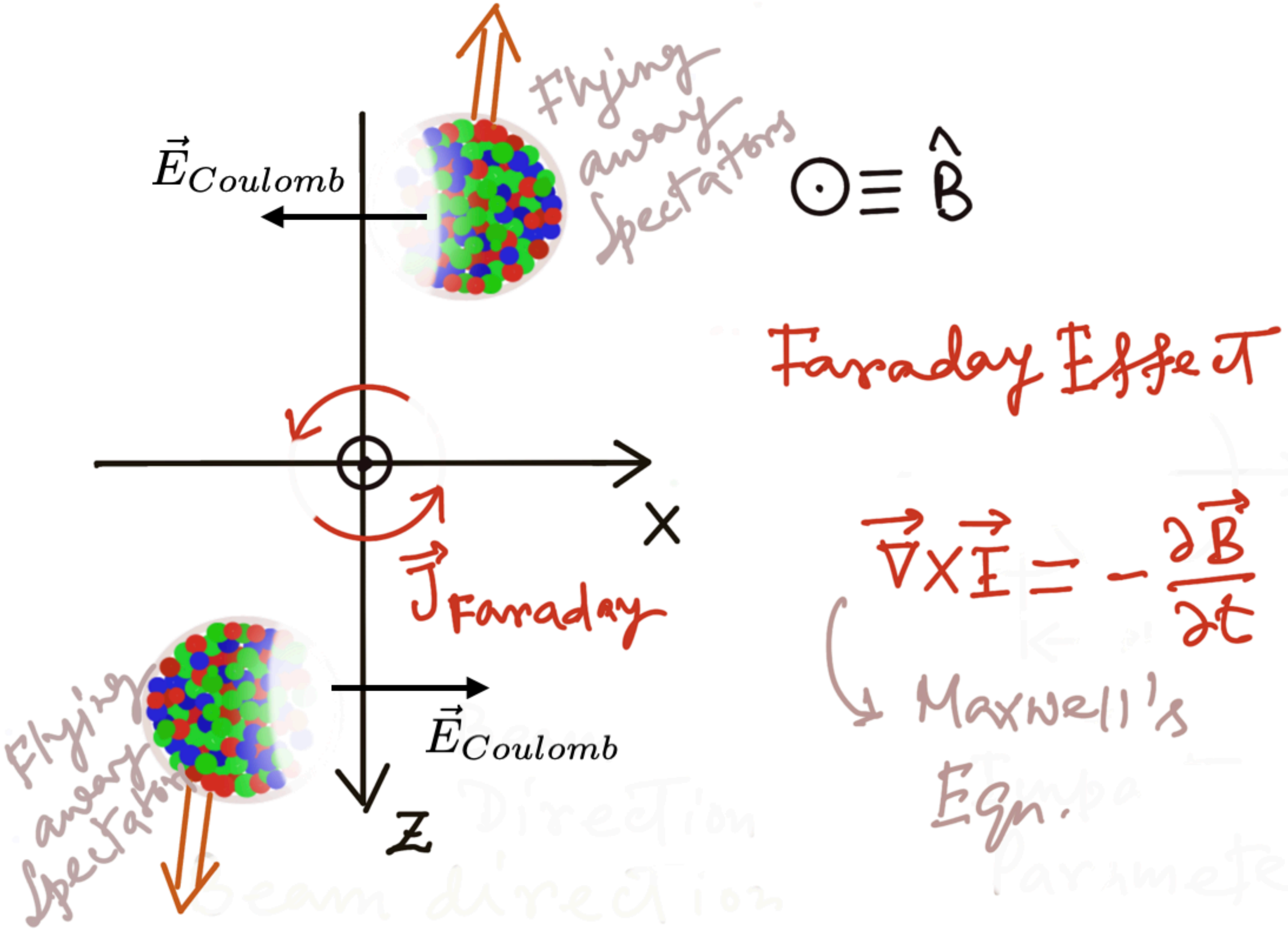
EM field drives splitting - Hall effect



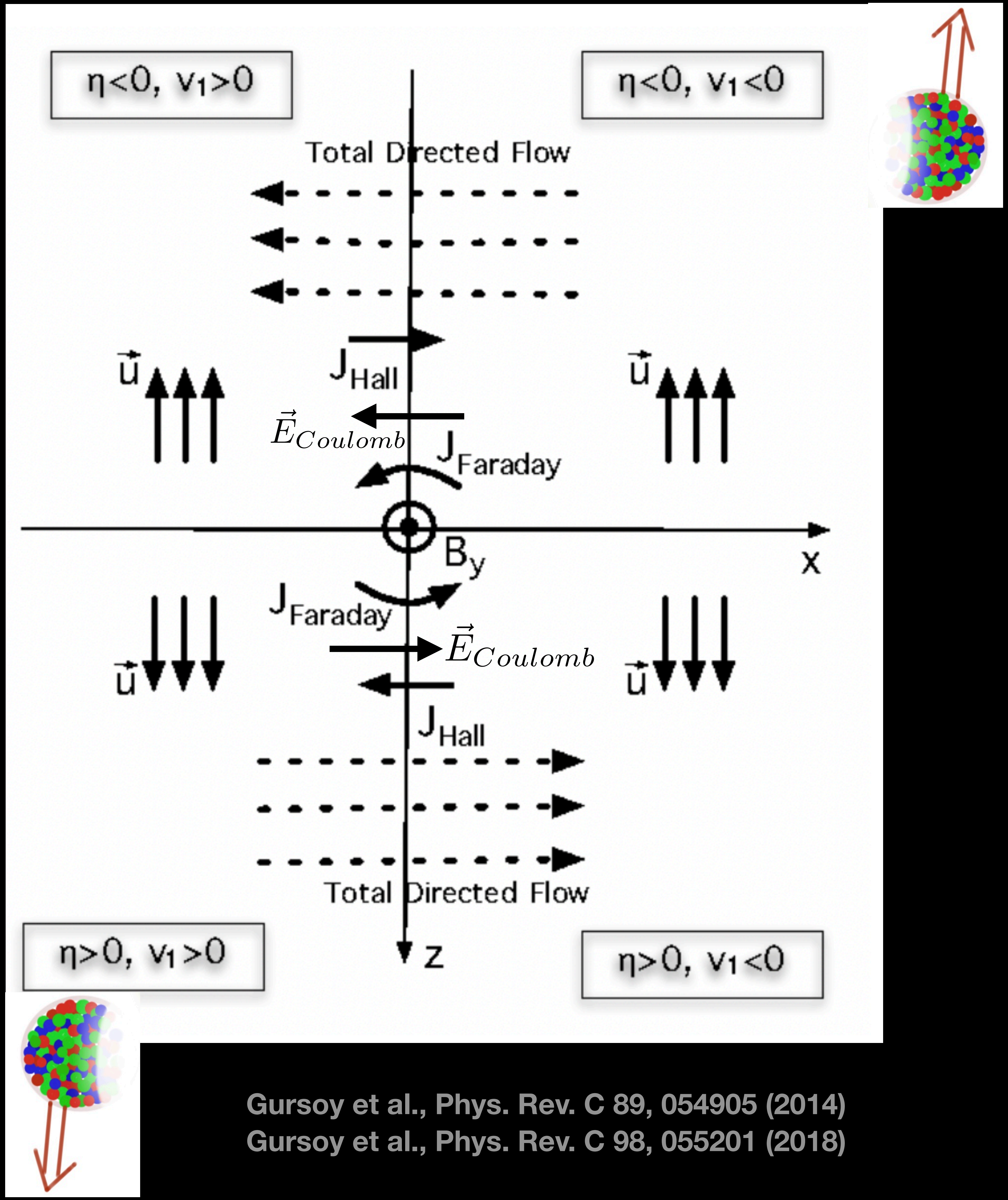
- Produced medium expands longitudinally ($\vec{u}||\hat{z}$, $\vec{u} \perp \vec{B}$)
- Lorentz force pushes positively and negatively charged particles in opposite directions
- Generated current $\perp \vec{B}, \vec{u}$ => Hall effect

EM field drives splitting - Faraday and Coulomb effect

- Spectators fly away, $\vec{B}$ decays down fast
- Time varying $\vec{B}$ induces $\vec{E}$ field => Faraday effect
- Charged spectators also generate Coulomb field



EM field drives splitting - Hall, Faraday and Coulomb effect

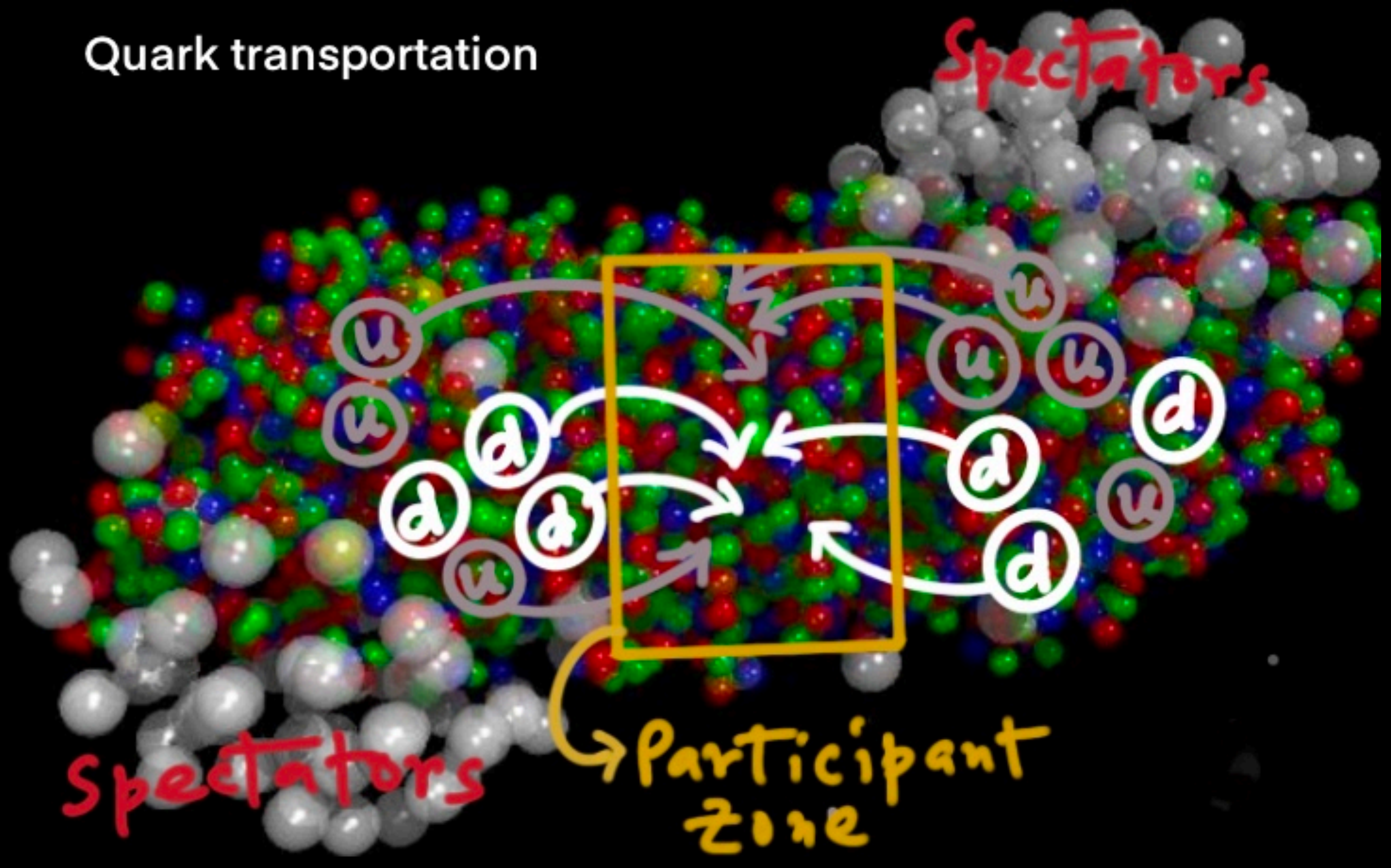


- Faraday, Coulomb and Hall are competing effects
- Net effect of Faraday, Hall and Coulomb affects v_1 and splitting between particles and antiparticles
- Direction of v_1 for positive particles shown by dashed arrows (when Faraday+Coulomb > Hall)
- Direction of v_1 for negative particles - the other way around
- EM field drives v_1 splitting (Δv_1) between particles and anti-particles
- Can we measure this splitting?

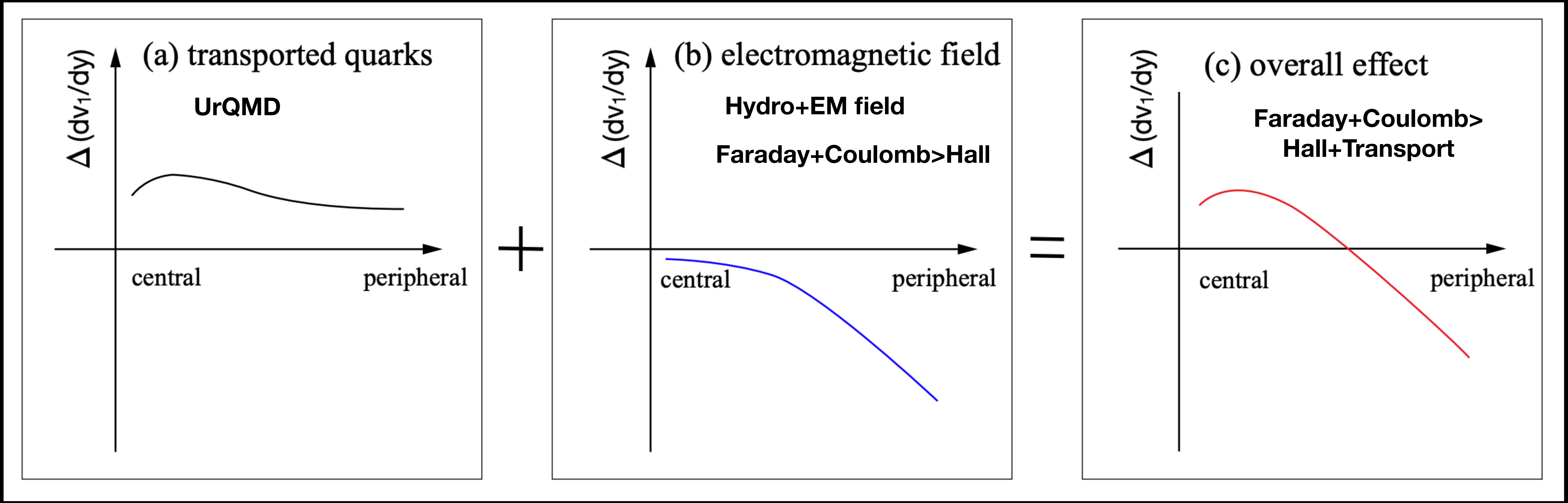
Gursoy et al., Phys. Rev. C 89, 054905 (2014)
Gursoy et al., Phys. Rev. C 98, 055201 (2018)

Splitting (Δv_1): Challenge in measurements (Transport)

- The u, d quarks can be transported from beam rapidity
- Transported quarks suffer a lot more interactions than produced quarks
- Transported quarks have different v_1 than produced quarks
- There is already a v_1 splitting between quarks (transported) and anti-quarks (produced)
- This splitting interferes with the EM field driven splitting becomes difficult to isolate



Splitting (Δv_1): Interplay between transport and EM field

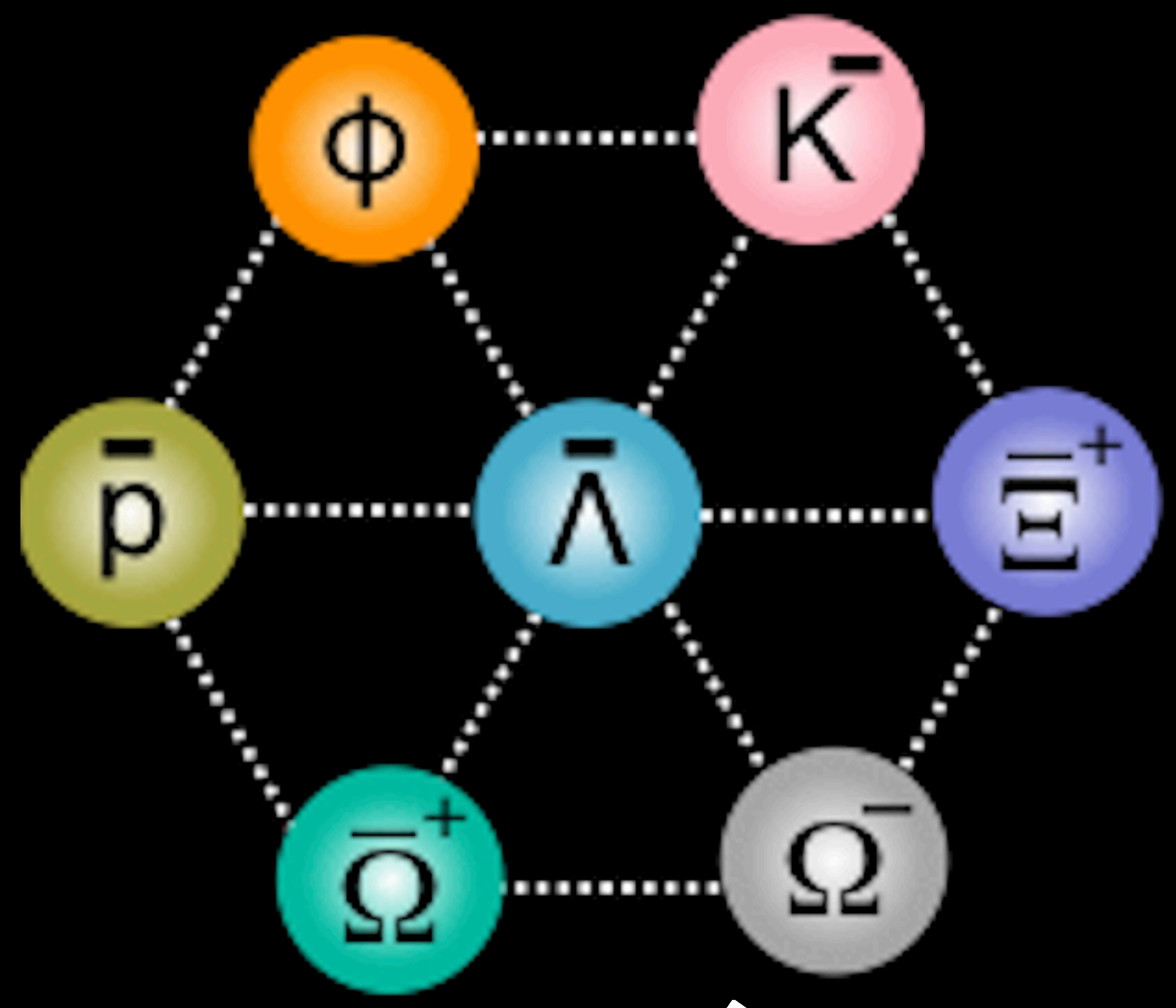


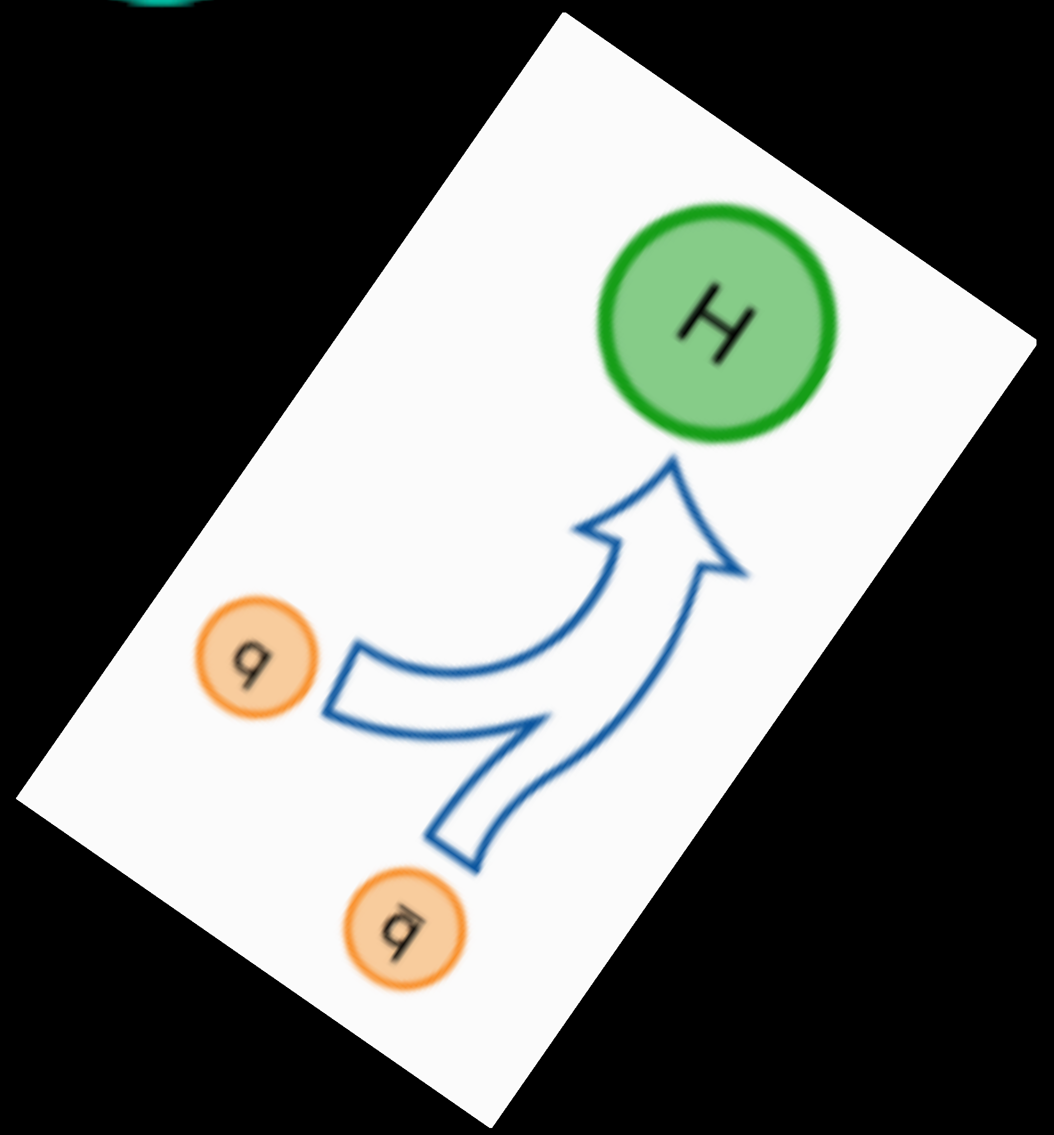
- Δv_1-slope difference between transported proton and anti-proton is positive (UrQMD expectation)
- This Δv_1-slope difference between proton and anti-proton is negative (Hydro+EMF expectation)
- These two effects convolute - Overall effect changes the sign
- This splitting acts as a background effect for EM-field-driven splitting — This background should be subtracted

Splitting (Δv_1): An approach to subtract transported quark effect

A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

- In experiment, it is impossible to distinguish between produced and transported u and d quarks
- Avoid particles containing u, d quarks
- Use only produced particles (only produced constituent quarks – $\bar{u}, \bar{d}, s, \bar{s}$): $K^-, \bar{p}, \bar{\Lambda}, \phi, \overline{\Xi}^+, \Omega^-$ and $\overline{\Omega}^+$
- With these particles, make a clean case to measure EM field-driven-splitting
- Combine different particles and compare the combinations with same mass at the constituent level
- Apply and test Coalescence-inspired sum rule: $v_1(hadron) = \sum v_1^i(q_i),$ (same $y - p_T/n_q$ space, with $n_q \rightarrow$ constituent quarks) $q_i \rightarrow$ Constituent quarks

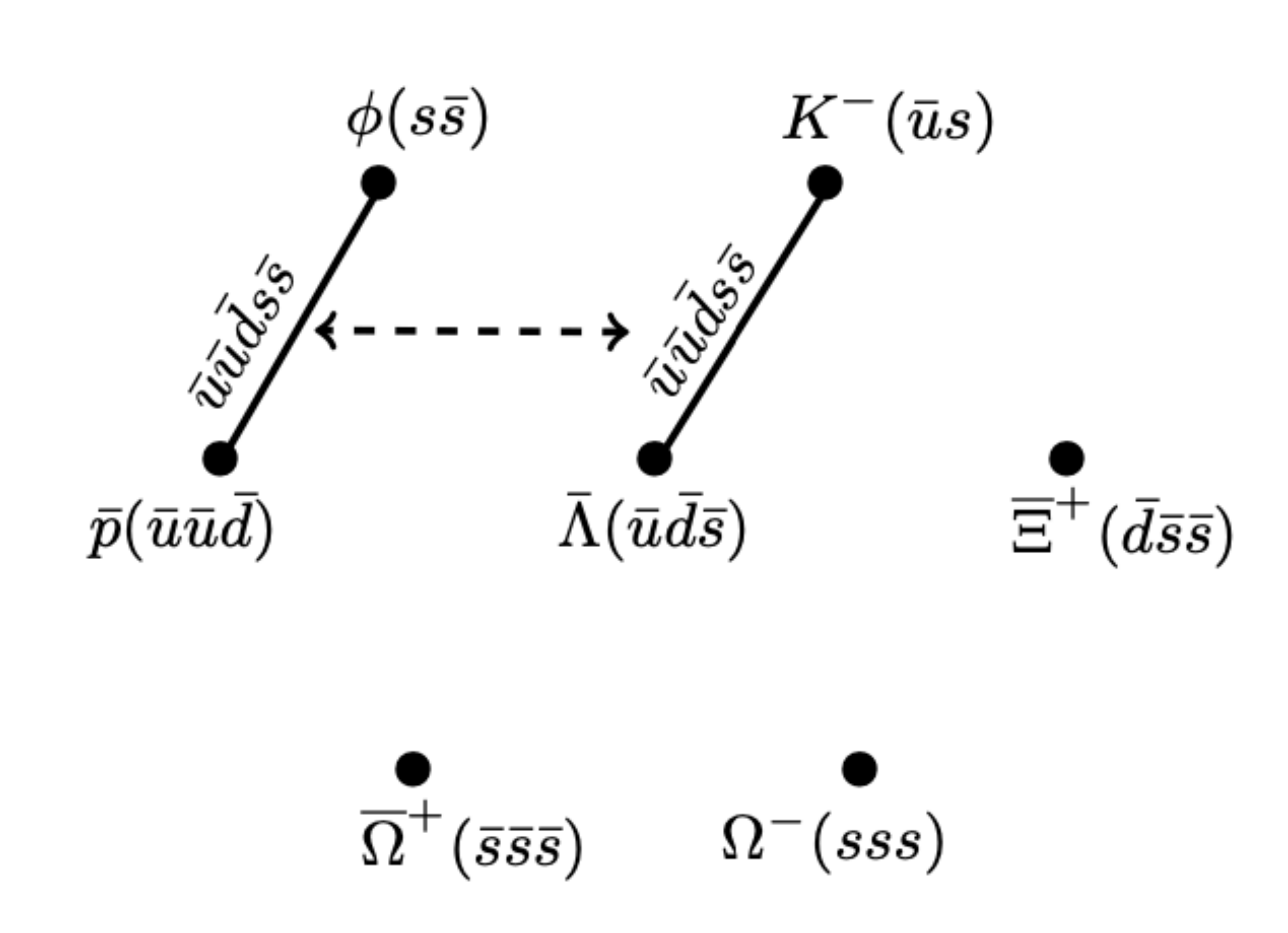




Splitting (Δv_1): Testing Coalescence sum rule

A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

- Combine particles and make identical quark combinations

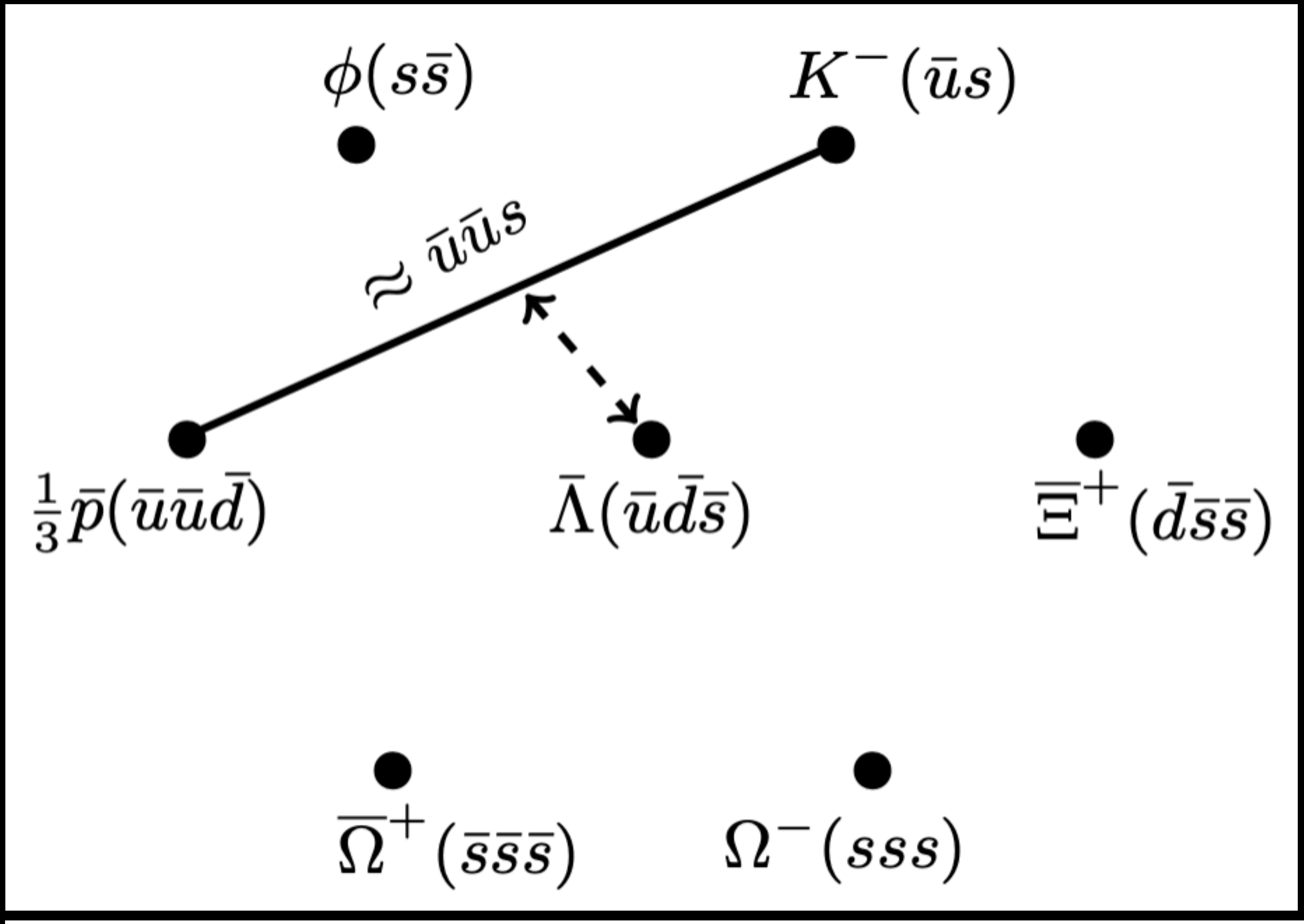


$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$$

- Charge difference, $\Delta q = 0$ and strangeness difference, $\Delta S = 0$

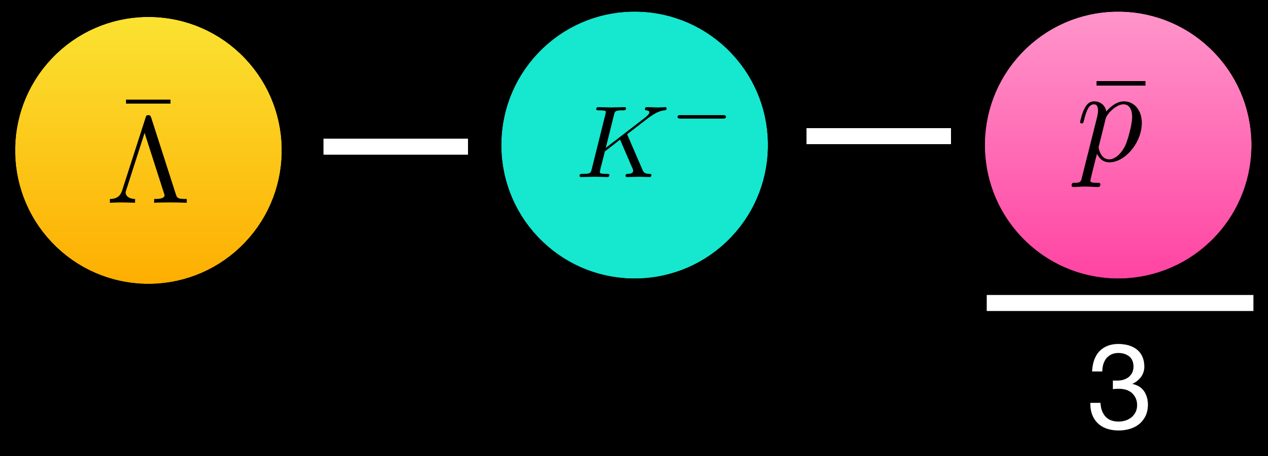
Splitting: Combination with non-zero Δq and ΔS

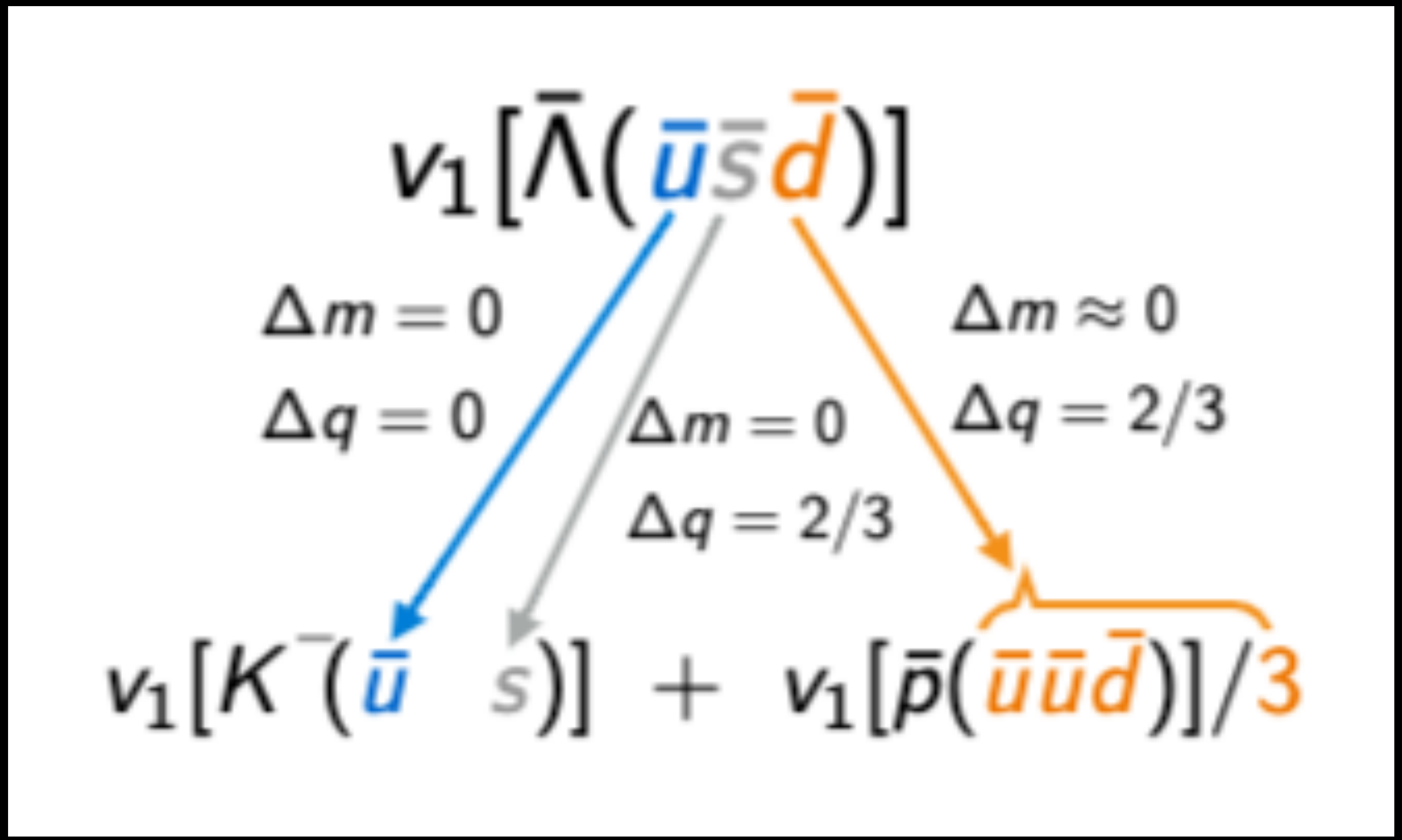
- Combine particles and make non-identical quark combinations, same mass at the constituent level



$$v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] \;\; \text{vs} \;\; v_1[K^-(\bar{u}s)] + \frac{1}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$$

A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)





- Charge difference, Δq = 4/3 and strangeness difference, ΔS = 2

Making more combinations

- Combinations having same or nearly same quark mass but different Δq and ΔS => No transported quark effect

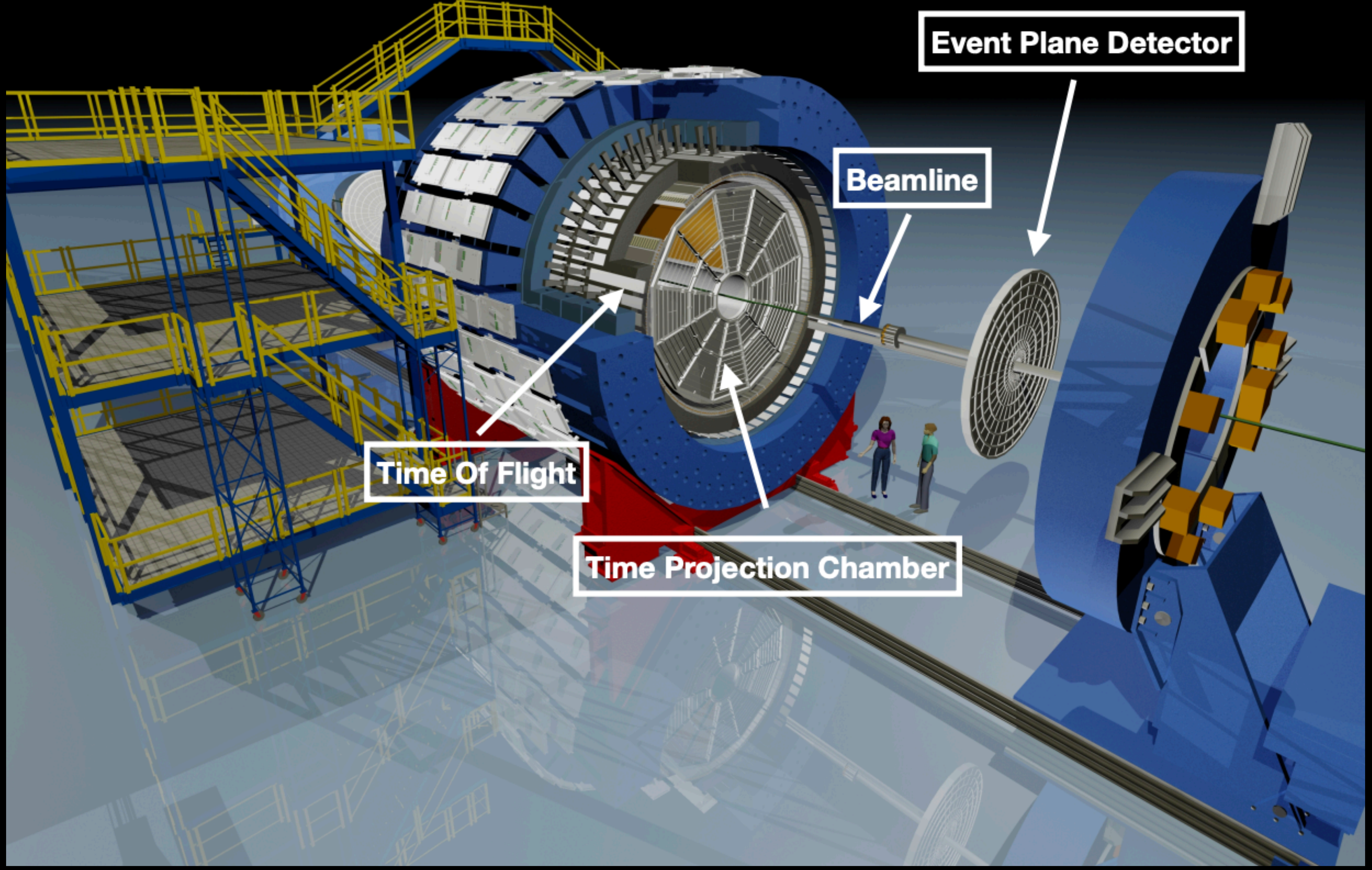
A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

Index	Quark Mass	Charge	Strangeness	Expression
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
5	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

- Only 5 combination differences among many are independent
- Two degenerate combinations in $\Delta S = 2$ - Good cross check
- Measure splitting with Δq and ΔS, though they are correlated

Towards measurements: STAR detector and datasets

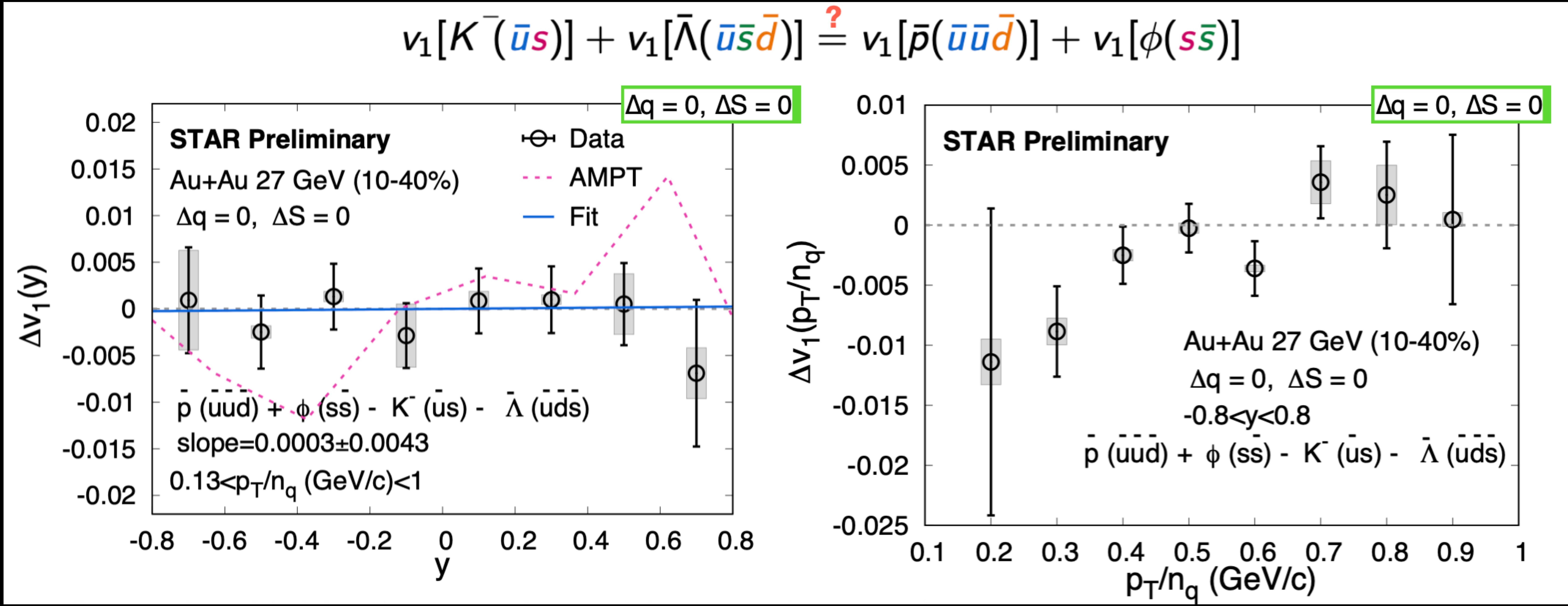
- TPC+TOF for PID: TPC measures dE/dx of tracks ($|\eta| < 1\,, 0 < \phi < 2\pi$) and TOF measures time of flight ($|\eta| < 0.9$)
- EPD ($2.1 < |\eta| < 5.1$) or ZDC ($|\eta| > 6.3$) for event plane reconstruction



Datasets analyzed:

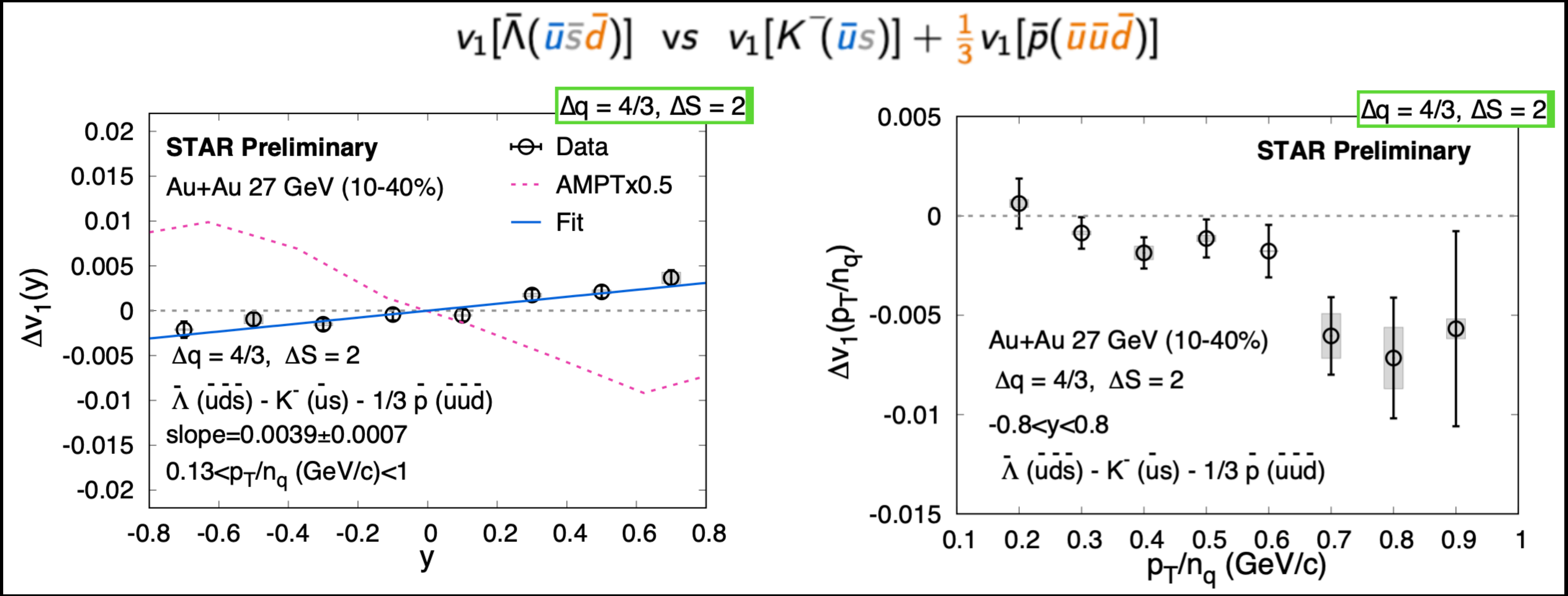
- At $\sqrt{s_{NN}} = 27$ GeV Au+Au at BES-II, and $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions

Coalescence sum rule at Au+Au @ 27 GeV



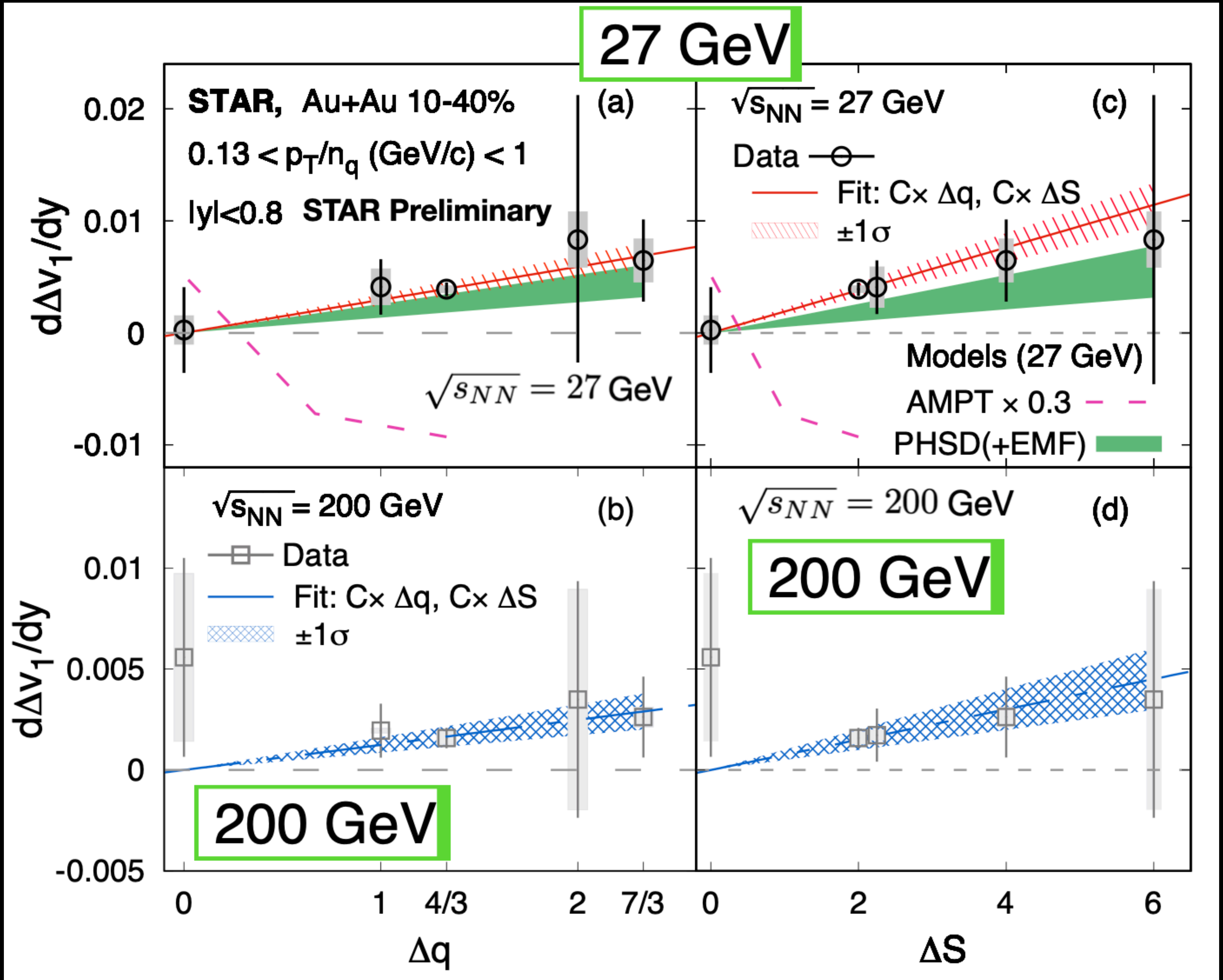
- Sum rule with identical quark combinations
- Δv_1 slope (with y) ~ 10^{-4}
- Sum rule holds within measured uncertainties

Splitting at non-zero Δq and ΔS (27 GeV)



- $|\Delta v_1|$ increases at larger y and pT/nq
- Significant non-zero slope (with y) for Δq = 4/3, ΔS = 2
- AMPT has the opposite trend - No EM field in AMPT

Splitting with charge and strangeness



- Δv_1 slope (fit constrained to origin) increases with Δq and ΔS
- Splitting increases going from $\sqrt{s_{NN}} =$ 200 to 27 GeV
- AMPT can not explain the data

  (Nayak et al., Phys. Rev. C 100, 054903 (2019))
- PHSD(+EMF) can describe the data within errors, but EMF is not the sole difference between these two models

Summary

- Heavy ion collisions are the tool to create QGP - primordial matter
- Strong EM field is produced in non-central collisions and can affect the directed flow splitting
- Discussed how to measure charge (Δq) and strangeness (ΔS) dependent directed flow splitting - free from the transported quark effect
- Measured splitting increases with Δq and ΔS, stronger in lower collision energy
- PHSD+EM field calculations can describe the charge-dependent splitting within uncertainties
- Produced EM field can lead to the splitting

Thank You 🙏