54th International Symposium on Multiparticle Dynamics (ISMD2026)

National Central University in Chungli, Taiwan

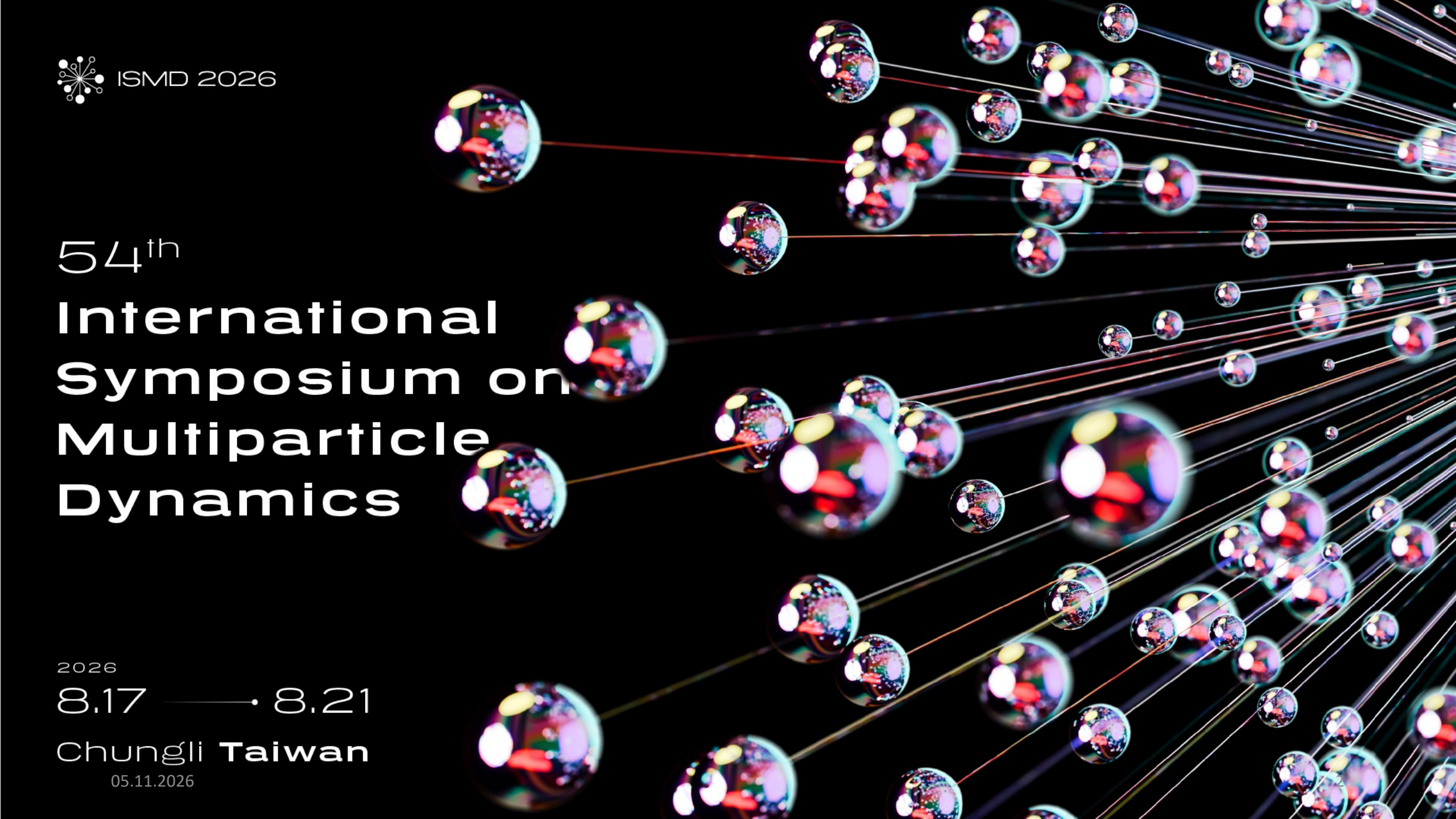
17.08-21.08.2026 (review)







https://indico.cern.ch/event/1593982/


ISMD 2026
54th
International Symposium on Multiparticle Dynamics
2026
8.17 — 8.21
Chungli Taiwan
05.11.2026


54th International Symposium
on Multiparticle Dynamics
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ISMD 2026


觀景台咖啡
54th International Symposium on Multiparticle Dynamics
ISMD 2026

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54th ISMD

August 17–21, 2026

National Central University, Chungli, Taiwan

118	14	9
Participants	Countries	Scientific Topics
102 in-person + 16 remote		All plenary
73	**9**	**13**
Oral presentations	Posters	Remote Presentations

Session	Convenors
Hot and Dense QCD Matter	Sanghoon Lim, Christopher Mc Ginn
Hadron Structure: PDFs, Small-x and Large-x Physics	Yong Zhao, Taisiya Mineeva
Hadron Spectroscopy, Exotic States, and Heavy Quark Physics	Su Houng Lee, Cameron Dean
BSM and New Developments in High Energy Physics and Nuclear Physics	Cheng-Wei Chiang, Hyunyong Kim
Cosmic Rays and Astroparticle Physics	Eva Santos, Anatoli Fedynitch
Detectors and Methods for High Energy Physics and Nuclear Physics	Akitomo Enokizono, Zhenyu Ye
Collectivity and Multiple Scattering	Giuliano Giacalone, Yuuka Kanakubo
Multiparticle Correlations and Fluctuations	Pulkit Agarwal, Yuko Sekiguchi
Forward and Diffractive Physics and Photon-Induced Processes	Wolfgang Schäfer, Christophe Royon
Poster	Itaru Nakagawa

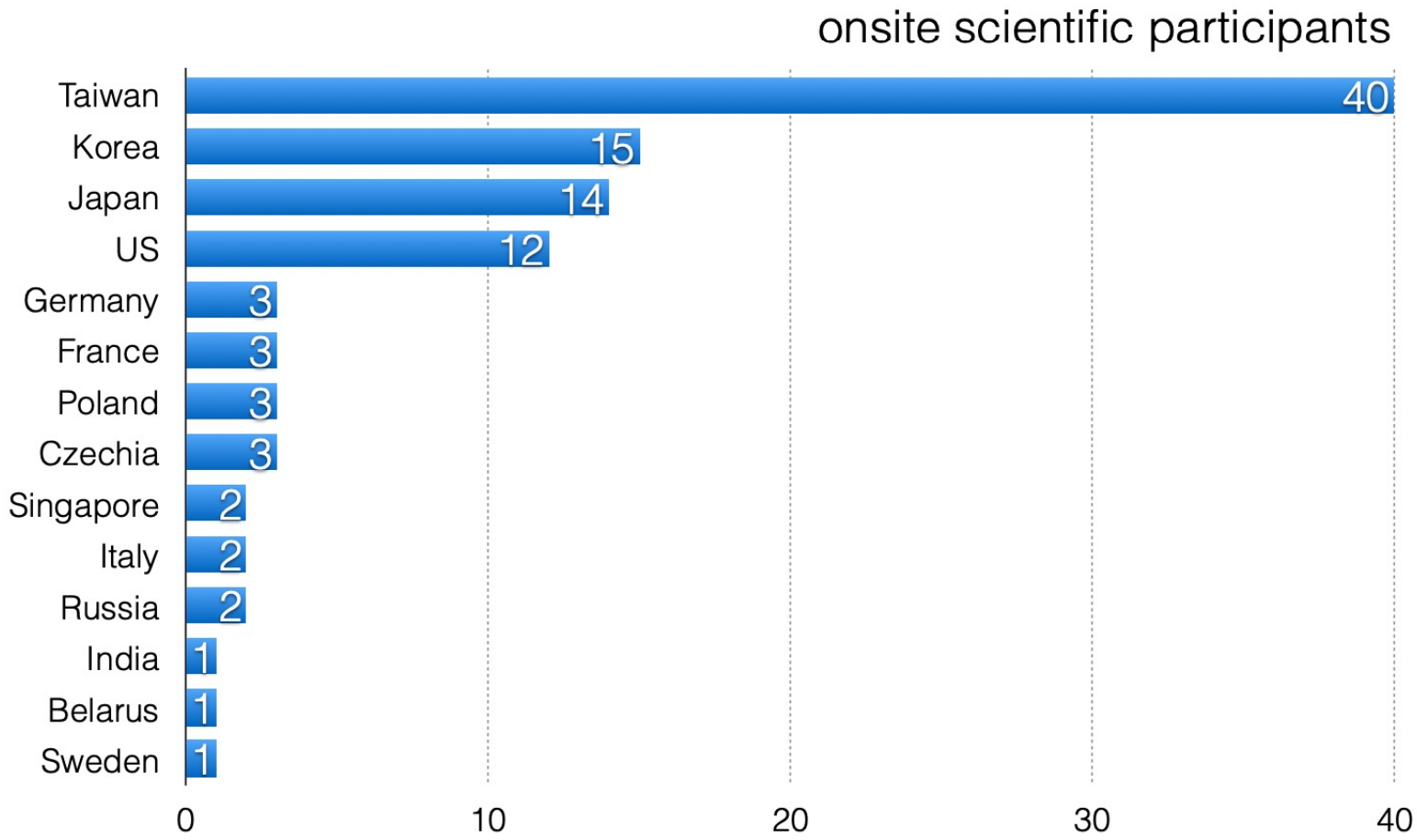
Presentation Statistics

- 73 oral presentations and 9 poster presentations
- including 13 remote presentations
- Two ANPhA Best Poster Awards have been established

Presentations



Participants (2/2)



Participants represented 14 countries, with strong participation from Korea, Japan, and the US.

Tom Trainor
University of Washington

Agenda

- Azimuth quadrupole – two contexts
- Pb-Pb quadrupole m_t spectra from $v_2(p_t)$
- SP spectrum two-component model (TCM)
- A-A geometry from mean-p_t data
- Model fits to 2D angular correlations
- Colour quadrupole radiation A-B trends
- Colour dipole (jets) radiation A-B trends

2512.08003 2607.25017 2510.05314

“elliptic flow” → quadrupole boost

В своем определении $v_2(p_t)$ основана на неявном предположении, что почти все образующиеся частицы исходят из одного источника. Предположение о наличии единственного доминирующего источника частиц в столкновениях A-A необоснованно. Исследование вариаций амплитуды квадруполя в p-p столкновениях с энергией 200 ГэВ демонстрирует, что структура квадруполя связана с новым процессом КХД, отдельным от диссоциации снаряда-нуклона и образования струи. Различимые компоненты адронов конечного состояния: (а) мягкая диссоциация снаряда-нуклона, (б) жесткая фрагментация рассеянных партонов в струи и (в) азимутальное квадрупольное излучение. [Т.Т. 2025]

Утверждение об образовании КГП на RHIC уже принято. Аналогичные явления проявились в меньших системах столкновений, где они были неожиданными. Первоначальная концепция, связанная с образованием КГП, была изменена введением концепции «капли КГП». Появилось всестороннее количественное описание явлений КХД во всех системах столкновений. В основе лежат процессы взаимодействия нескольких глюонов, создающие характерные корреляционные структуры, соответствующие цветному дипольному (2-g, di-jet) и цветному квадрупольному (3-g) излучению. Это описание применяет одни и те же правила единообразно к малым и большим системам столкновений. [2610.12882] ”Undiscovering Quark-gluon Plasma” T. Trainor. “… описывается взлет и падение коллективных усилий по созданию КГП в лаборатории и изучению её свойств.”

Azimuth Quadrupole – Two Contexts

Poskanzer and Voloshin, 1998

based on Bevalac sphericity tensor

"ideal hydro"

$$v_2(p_t) \equiv \frac{\int_0^{2\pi} d\phi_r \cos(2\phi_r)\bar{\rho}(p_t, \Delta y_t(\phi_r))}{\int_0^{2\pi} d\phi_r \bar{\rho}(p_t, \Delta y_t(\phi_r))}$$

common $\bar{\rho}(p_t, \Delta y_t(\phi_r))$

wrong premise

what is assumed:

$$\rightarrow ? \langle \cos(2\phi_r) \rangle (p_t)$$

single-component model

conjectured dense flowing medium

reaction plane assumed

boost: $\Delta y_t(\phi_r)$ -- flow field on rapidity y_t

TCM 0803.4002

what is measured: **pairs**

$$v_2(p_t) \neq \langle \cos(2\phi_r) \rangle (p_t)$$

real HEP world:

$$= \frac{V_2\{2D\}(p_t) + \text{jet contribution (nonflow)}}{(N_{part}/2) S_{NN}(p_t) + N_{bin} H_{NN}(p_t)}$$

$= \bar{\rho}_0(p_t)$

SP spectrum

TCM

2D model fits on (η,ϕ)

no reaction plane

empirical

Quadrupole *Source* Field

0803.4002

what radiates quadrupole hadrons?

18 years

two-particle correlations

hadron species *i*

$$v_2(p_t) = \frac{V_2(p_t)}{(N_{part}/2)S_{NN}(p_t) + N_{bin}H_{NN}(p_t)} \longleftrightarrow = \bar{\rho}_0(p_t)$$ SP spectrum

Fourier amplitude:

measured

$$V_{2i}(p_t) \rightarrow V_{2i}(y_{ti}) \approx \bar{\rho}_{0i}(y_{ti}) v_{2i}(y_{ti})$$

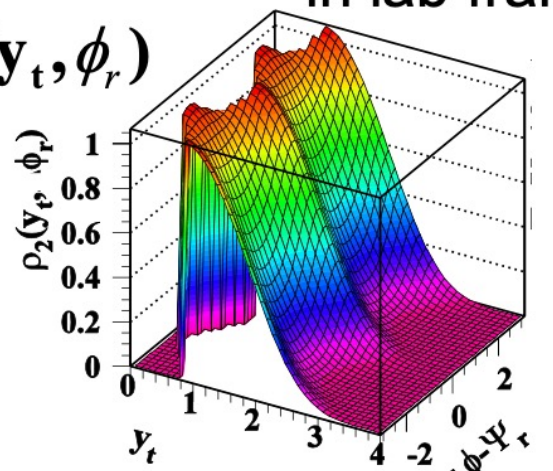
$$y_{ti} = \ln[(m_{ti} + p_t)/m_i]$$

inverse problem

$$\equiv \frac{1}{2\pi}\int_{-\pi}^{\pi} d\phi_r \cos(2\phi_r)\, \bar{\rho}_{2i}(y_{ti}, \phi_r)$$?

in lab frame

$\bar{\rho}_2(y_t, \phi_r)$



boosted radiation

$\phi_r = \phi - \Psi_r$

simplest source:

Boltzmann exponential on m_t'

$$m'_{ti} = m_i \cosh(y'_{ti})$$

boost frame

$$\bar{\rho}_{2i}(y_{ti}, \phi_r) \propto \exp\{-(m_i/T_2)[\cosh(y_{ti} - \Delta y_t(\phi_r)) - 1]\}$$

y'_{ti}

boost model: $\Delta y_t(\phi_r) = \Delta y_{t0} + \Delta y_{t2}\cos(2\phi_r)$

monopole quadrupole

Quadrupole Spectra in the Boost Frame

2512.08003

Jacobian

$$\bar{\rho}_{2i}(m'_{ti}) \approx (y'_{ti} / m'_{ti}p'_{ti})\bar{\rho}_{2i}(y'_{ti})$$

$\hat{S}_2(m'_t)$ spectrum model

$$\bar{\rho}_{2i}(m'_{ti}) \propto \hat{S}_2(m'_{ti})$$

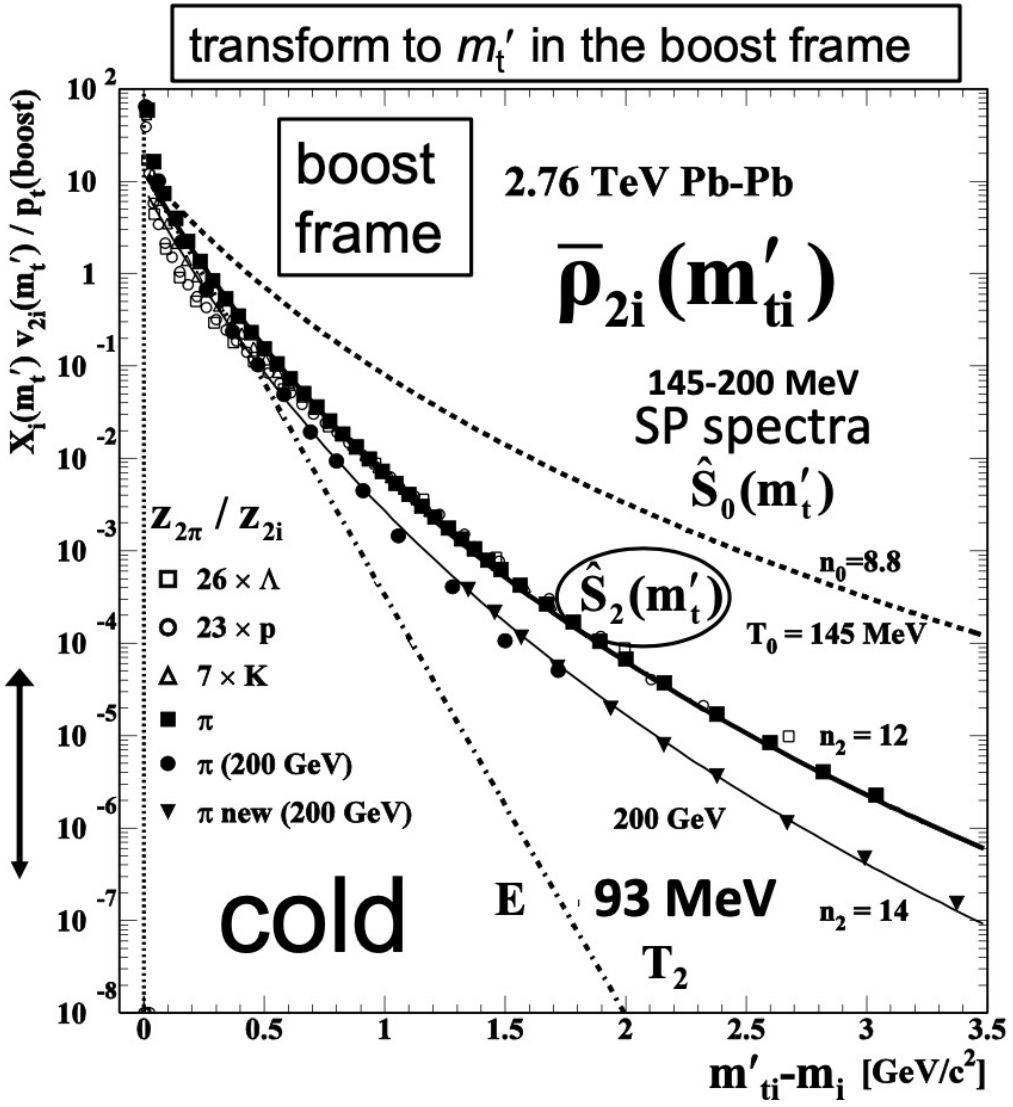
back transformed, *predicts* all $v_{2i}(p_t)$ data

quadrupole spectra distinct from single-particle spectra

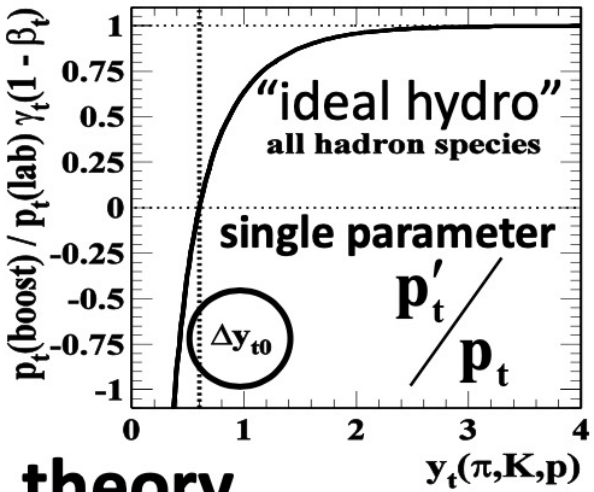
four hadron species coincide

seven orders of magnitude

$$\hat{S}_2(m'_t) \neq \hat{S}_0(m'_t)$$



Viscous-hydro Theory vs few-gluon Interactions



relativistic kinematics

2512.08003

v_2 as defined

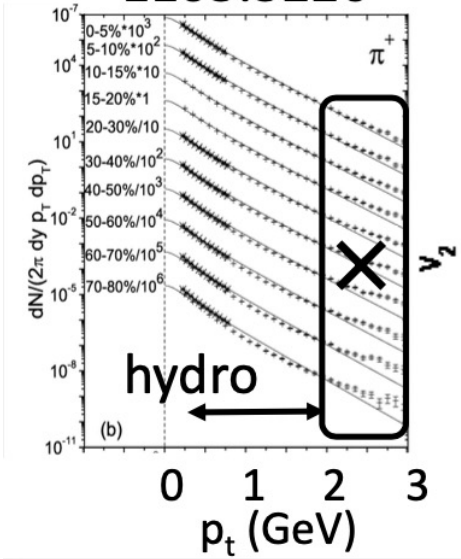
$$\frac{v_2(p_t)}{p_t} \approx \frac{p'_t}{p_t}\frac{\Delta y_{t2}}{T_2}\frac{\bar{\rho}_2(p_t)}{\bar{\rho}_0(p_t)}$$

quadrupole

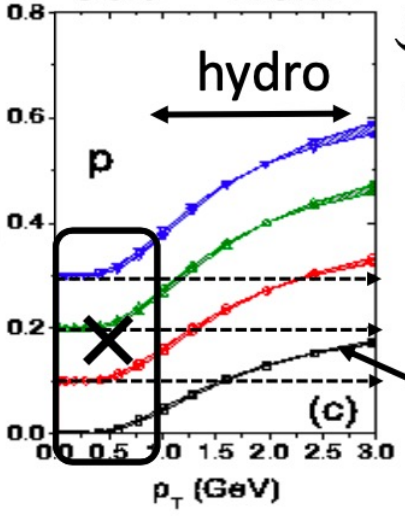
TCM

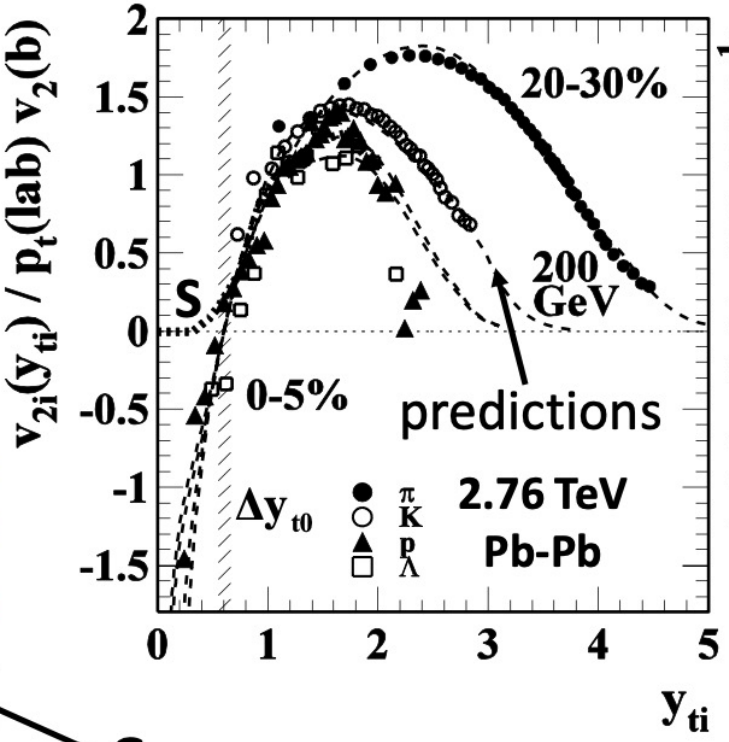
theory

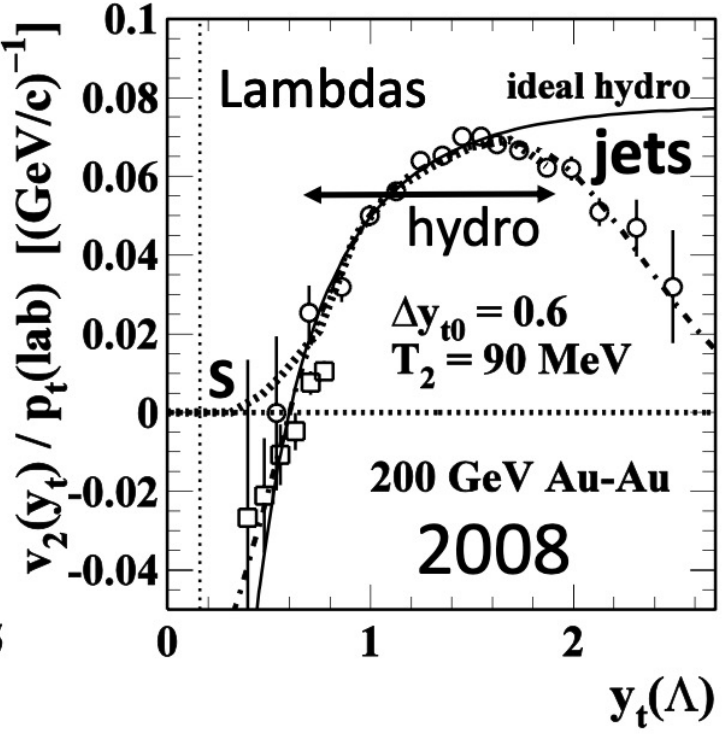
1105.3226



OSU -- Heinz







S

10-20%

hydro theory is irrelevant

TCM *Required* by SP Spectrum Data

jets

13 TeV *p-p*

2607.25017

ALICE 1908.01861

$\bar{\rho}_{si} = \bar{\rho}_{0i} / (1 + \tilde{z}_i xv)$

hadron species *i*

$y_{t\pi} \equiv \ln[(p_t + m_{t\pi}) / m_\pi]$

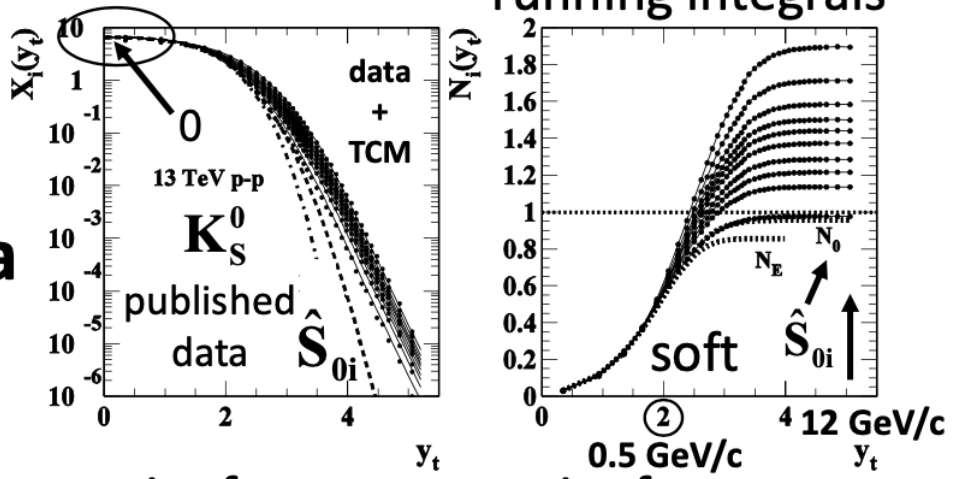
xv?

entire spectra

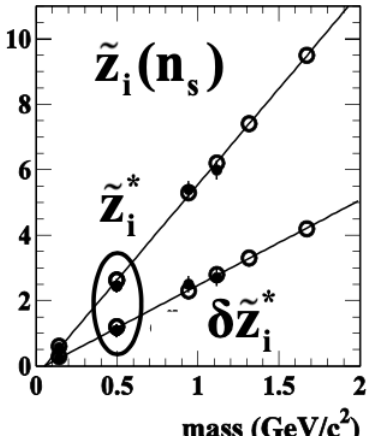
$X_i(p_t) = \bar{\rho}_{0i}(p_t) / \bar{\rho}_{si}$

$Y_i(p_t) = X_i(p_t) - \hat{S}_{0i}(p_t)$

running integrals



mass only



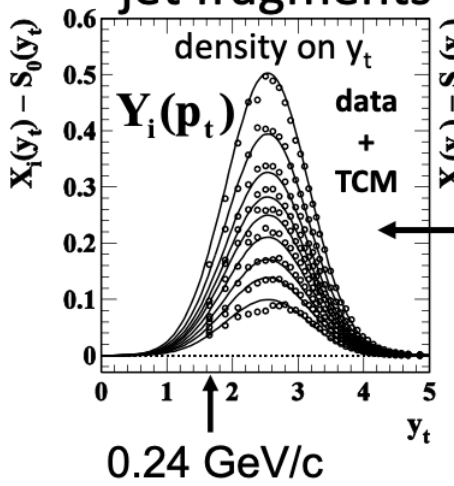
jets

AA hard/soft ratio **?**

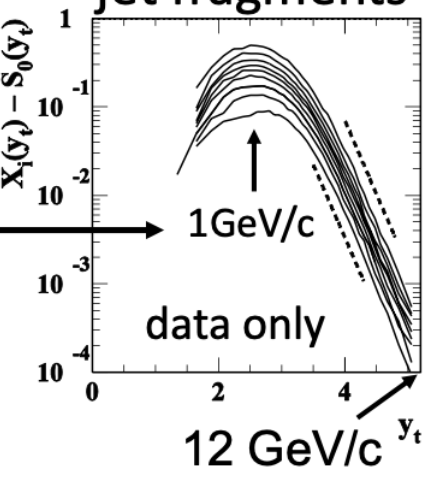
$$xv \equiv \frac{\rho_h}{\rho_s} = \frac{\rho_{hNN}}{\rho_{sNN}} \frac{N_{bin}}{(N_{part}/2)}$$

x $\quad$ v

jet fragments



jet fragments



no hydro

Quadrupole/Dipole A-B Summary

- **Assumption of lone particle source for *ratio* "*v2*" is wrong**
- **SP spectra at lower p_t dominated by jets, not flows**
- **No evidence for dense QCD medium or "jet quenching"**
- **No relevance for hydro theory models (обоснованность)**
- **Few-gluon interactions are fundamental within A-B**
- ***p-p* 2D correlations + *jet-based* A-A geometry *predict***
- **Color quadrupole radiation trends (over 10^6 range)**
- **Color dipole (jet) radiation trends (over 10^4 range)**

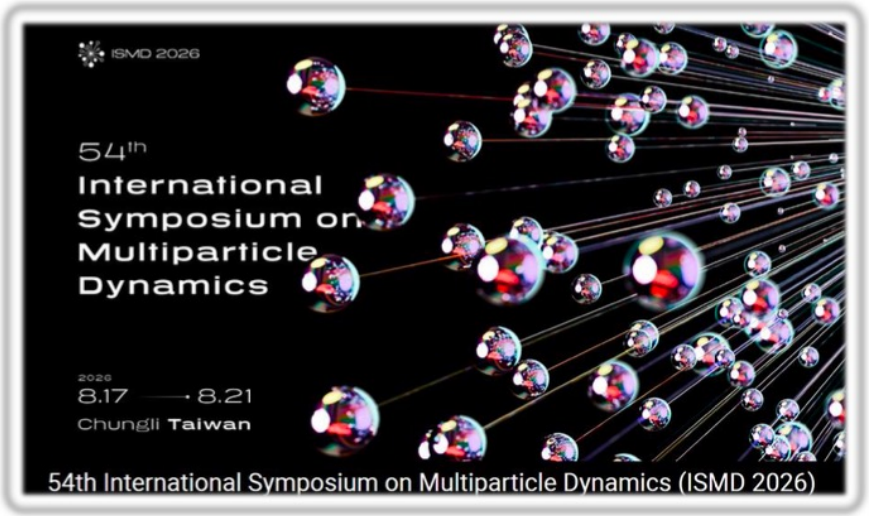
[0708.0792] the azimuth quadrupole may be a manifestation of "gluonic multipole radiation"

A higher-harmonic observable for the chiral magnetic effect in heavy-ion collisions

Based on: H. Li *et al*. arXiv:2605.25487

Han-Sheng Li

(Purdue University)



54th International Symposium on Multiparticle Dynamics (ISMD 2026)

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Outline

- The Chiral Magnetic Effect (CME)
- Observables in Heavy Ion collisions
- Flow-induced background and Higher order components
- Physics models and Revisit flow background
- Results and discussions
- Summary

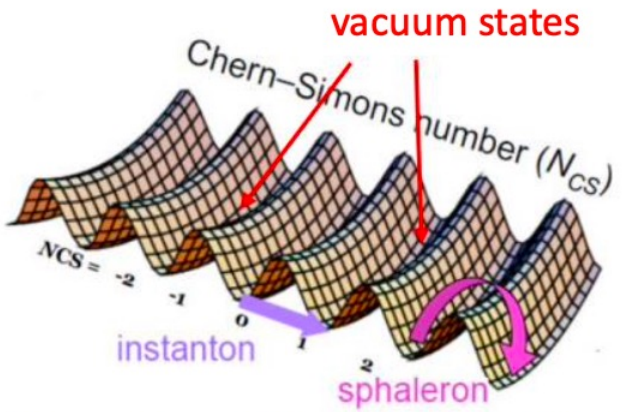
The Chiral Magnetic Effect (CME)

The CME

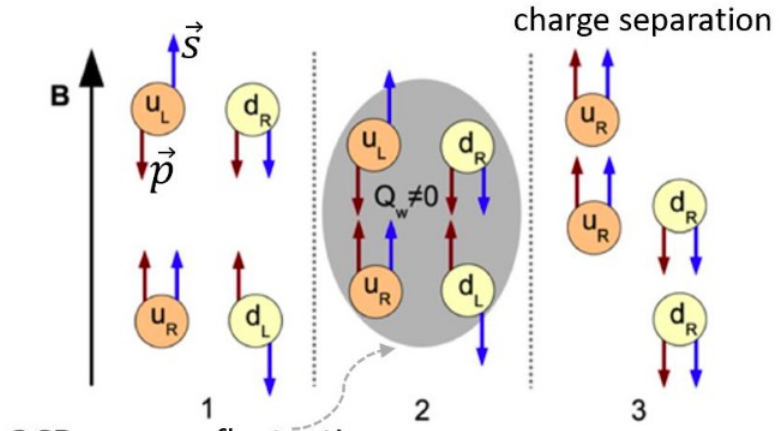
- QCD Vacuum fluctuations → Non-zero topological charge → Chirality imbalance
- Strong magnetic field → (anti-) parallel to B → Charge separation

Importance of the CME

- Approximate chiral symmetry restoration
- Local P/CP-violation in strong interaction
- It may resolve the strong CP problem of matter–antimatter asymmetry



Kharzeev,Pisarski,Tytgat,PRL81(1998)512



QCD vacuum fluctuation

Topological charge $Q_w \propto \int \vec{E}_c \cdot \vec{B}_c$

Observables in Heavy Ion collisions

Fourier series of particle azimuthal distributions

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2v_1\cos(\phi - \Psi_{\mathrm{RP}}) + 2a_{1\pm}\sin(\phi - \Psi_{\mathrm{RP}}) + 2v_2\cos 2(\phi - \Psi_{\mathrm{RP}}) + \cdots$$

Elliptic flow

$$v_2 = \langle \cos 2(\phi - \Psi_{\mathrm{RP}}) \rangle$$

CME

$$a_1 = \langle \sin(\phi - \Psi_{\mathrm{RP}}) \rangle$$

Parity odd, $\langle a_1 \rangle = 0$

γ correlator

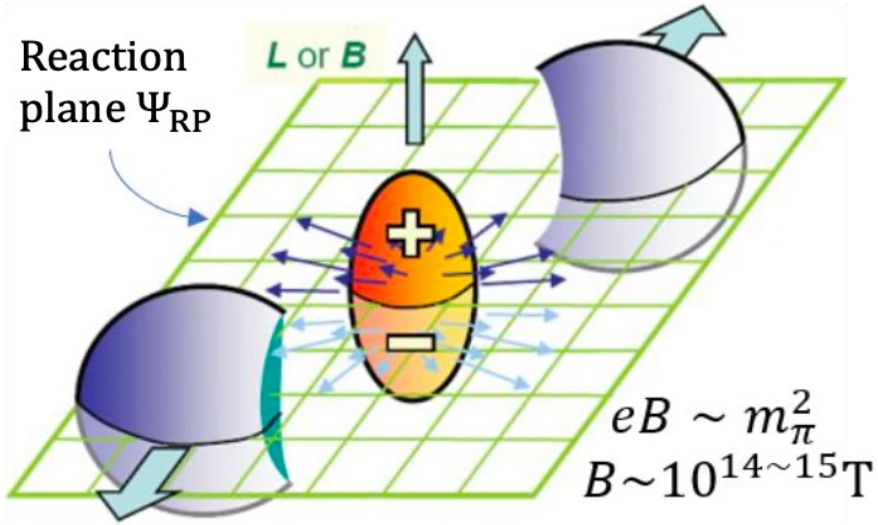
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle$$

CME signal of γ

$$\begin{pmatrix} \gamma_{\mathrm{OS}} = 2 \cdot a_{1,+}a_{1,-} = \langle a_1^2 \rangle \\ \gamma_{\mathrm{SS}} = a_{1,+}a_{1,+} + a_{1,-}a_{1,-} = -\langle a_1^2 \rangle \\ \Delta\gamma = 2\langle a_1^2 \rangle \quad \text{Parity even} \end{pmatrix}$$

S.A. Voloshin, Phys. Rev. C70(2004)057901

D. E. Kharzeev, Progressin Particle and Nuclear Physics, vol. 75, pp. 133–151, 2014

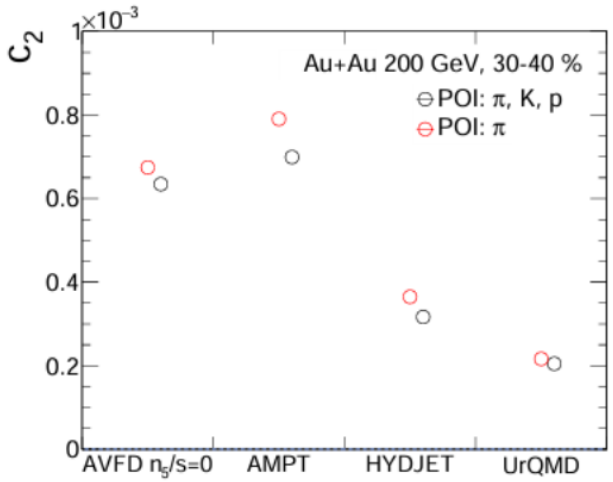


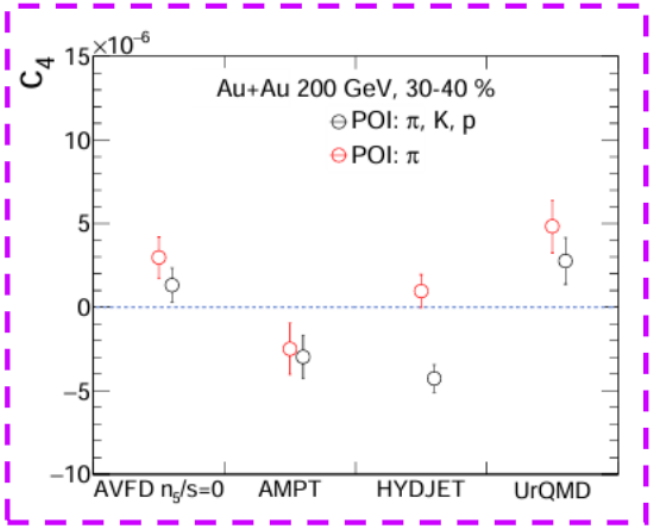
Physics models

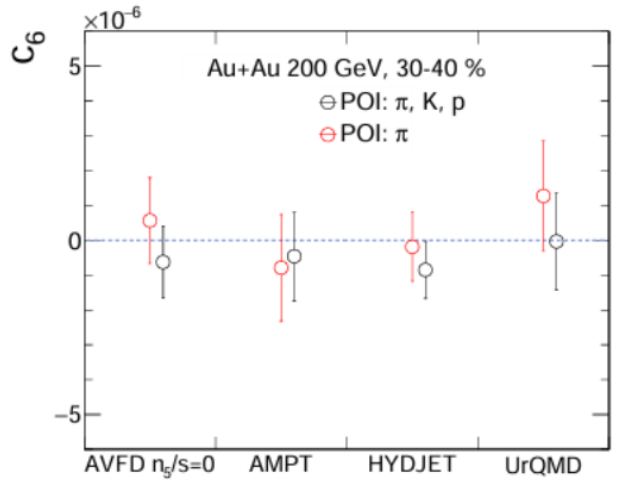
Fit modulations (AMPT, HYDJET, UrQMD)

s_n are consistent with zero

ϕ_α and ϕ_β - the azimuthal angles of two particles of interest (POI)







- The high-order harmonic component c_4 is small but seems nonzero

Summary

- CME produces a finite hexadecapole component c_4 in the $\Delta\gamma(\phi_{\mathrm{pair}})$ distribution in AVFD, presumably due to magnetic field fluctuations
- Background to c_4 is expected from azimuthal-dependent cluster correlations, but generally small
- c_4 and $c_4/\,c_2$ are viable CME observables to search for the CME



Institute of Physics, Academia Sinica



Local Spin Polarization by color-field correlators and momentum anisotropy

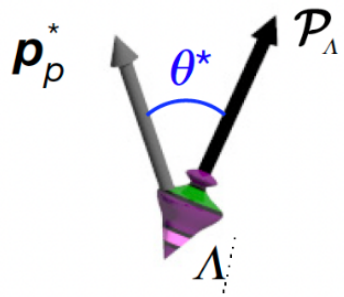
Haesom Sung
Berndt Müller, and Di-Lun Yang

Haesom Sung, Berndt Müller, Di-Lun Yang, arXiv:2507.23210v3

Motivation

Λ Global Polarization

$$\Lambda \rightarrow p + \pi^-$$



Λ polarization vector

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathbf{P}_\Lambda \cdot \hat{\mathbf{p}}_p^*) = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathbf{P}_\Lambda \cos\theta^*)$$

proton momentum unit vector

The proton tends to be emitted along the spin direction of the Λ with probability (opposite for antiparticle)

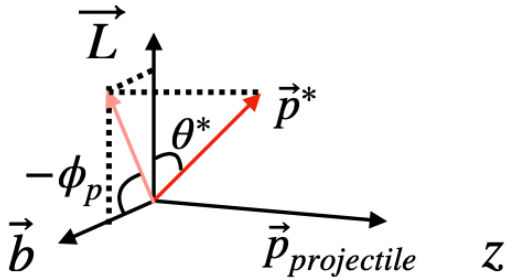
$$\Rightarrow \mathbf{P}_\Lambda = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle \cos^2\theta_p^* \rangle}$$

$\mathbf{P}_\Lambda$ = hyperon polarization vector

α_Λ = hyperson decay parameter

$(\alpha_\Lambda = 0.750, \alpha_{\bar{\Lambda}} = -0.758)$ **BESIII Collaboration**, Nature Phys, 15(2019) 631-634

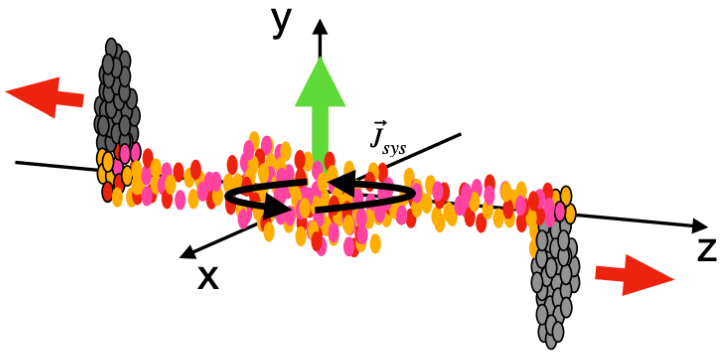
$\hat{p}_p^*$ = unit vector along proton(dauther baryon) momentum



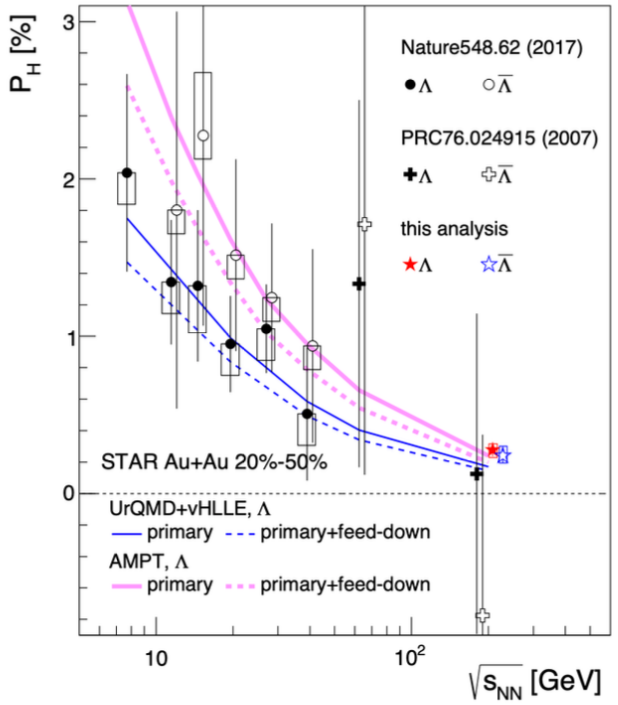
В столкновениях RHI из-за эффекта glasma результирующий спектр продольной поляризации $\Lambda/\bar{\Lambda}$-гиперонов имеет синусоидальную структуру с удвоенным азимутальным углом относительно p_t. Локальная спиновая поляризация (LSP) кварков, индуцированная корреляторами цветового поля, возникающими из корреляции хромо-лоренцевой силы и хромо-магнитной поляризации или хромоспинового эффекта Холла в присутствии анизотропии импульса. Эти эффекты могут вызывать продольную поляризацию из флуктуирующих цветовых полей в фазах glasma или QGP с поперечным расширением в анизотропном направлении. Оценка порядка величины эффекта согласуется с экспериментальными наблюдениями. Когерентные глюонные поля могут быть новым источником спиновой поляризации в RHI.

Motivation

Λ Global Polarization



L. Adamczyk et al. (STAR), Nature 548, 62 (2017)
J. Adam et al. (STAR), Phys. Rev. C 98, 014910(2018)]
S. Acharya et al. (ALICE), Phys. Rev. C 101, 044611 (2020)



UrQMD+vHLLE: **I. Karpenko, et al,** Eur. Phys. J. C 77, 213 (2017)
AMPT: **H. Li, et al,** Phys. Rev. C 96, 054908 (2017)

Cooper-Frye formula

F. Becattini, et al., Ann. Phys. 338, 32 (2013)
R. Fang, et al., PRC 94, 024904 (2016)

$$P^{\mu}_{\varpi} = \epsilon^{\mu\rho\sigma\tau} p_{\tau} \frac{\int_{\Sigma} d\Sigma \cdot p n_F (1 - n_F) \varpi_{\rho\sigma}}{\int_{\Sigma} d\Sigma \cdot p n_F}$$

$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu}) : \textbf{thermal vorticity}$$

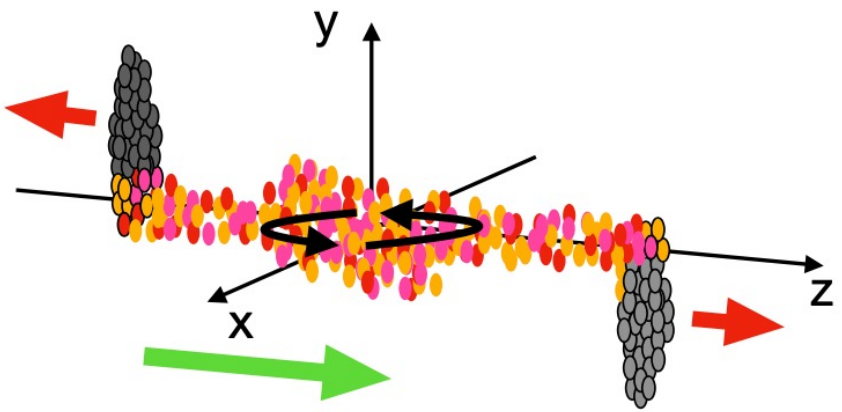
Global polarization from vorticity

F. Becattini et al., PRC95, 054902 (2017)

$$P_{\Lambda} = \int_{p} P^{-y}(p) \simeq \frac{\omega}{2T} \qquad \omega \simeq 0.02\,\mathrm{fm}^{-1}$$

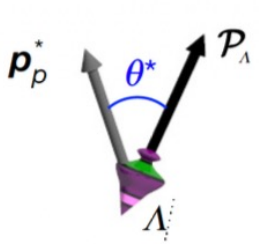
A widely accepted hypothesis suggests that the substantial angular momentum in peripheral collisions leads to the spin polarization of quarks and gluons via spin-orbit coupling, the polarization subsequently being transferred to hadrons during hadronization and freeze-out.

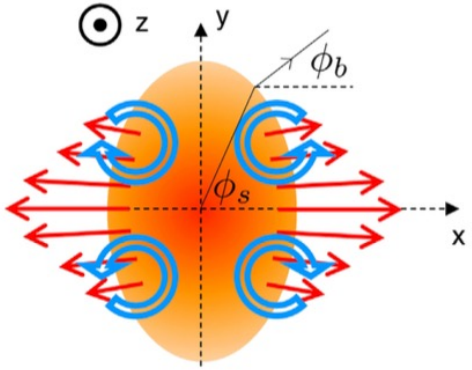
Motivation
Longitudinal Polarization



P^z

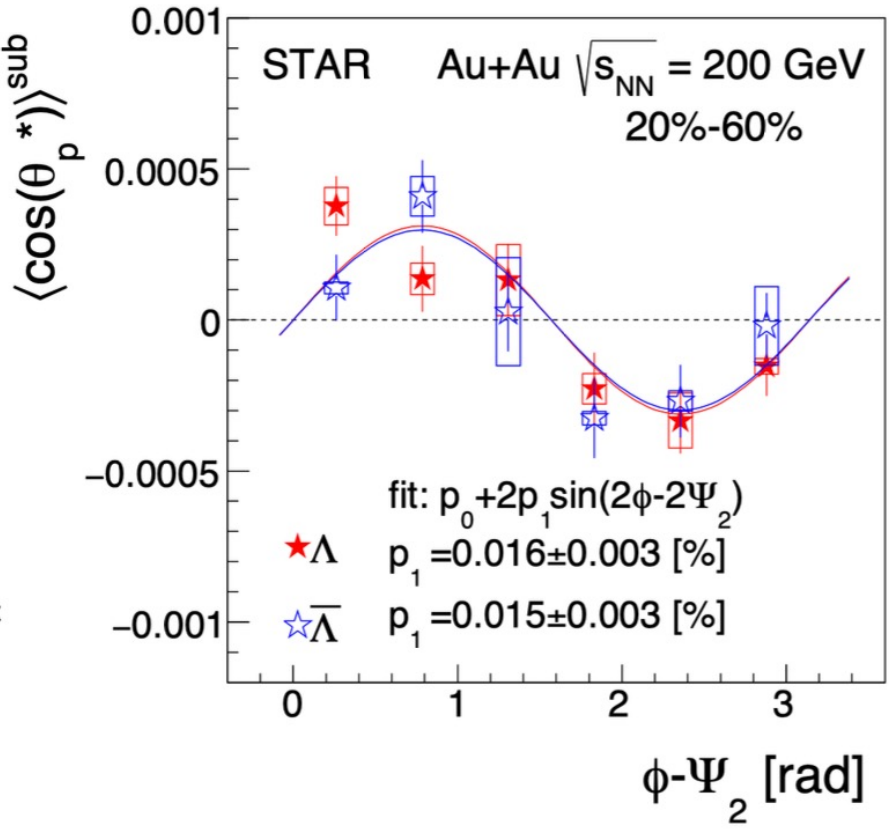
$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle \cos^2\theta_p^* \rangle}$$





A **sinusoidal** structure of longitudinal Λ polarization with azimuthal angle

J. Adam et al. (STAR), PRL. 123 (2019) 13, 132301



Longitudinal Local Polarization

Hydrodynamic with Thermal Vorticity & Shear effect

Thermal shear эффект - описывает генерацию спиновой поляризации частиц за счет градиентов скорости и температуры в расширяющейся КГП

$$S^\mu = S^\mu_\varpi + S^\mu_\xi$$

Vorticity and shear effect have **opposite signs**

Thermal vorticity

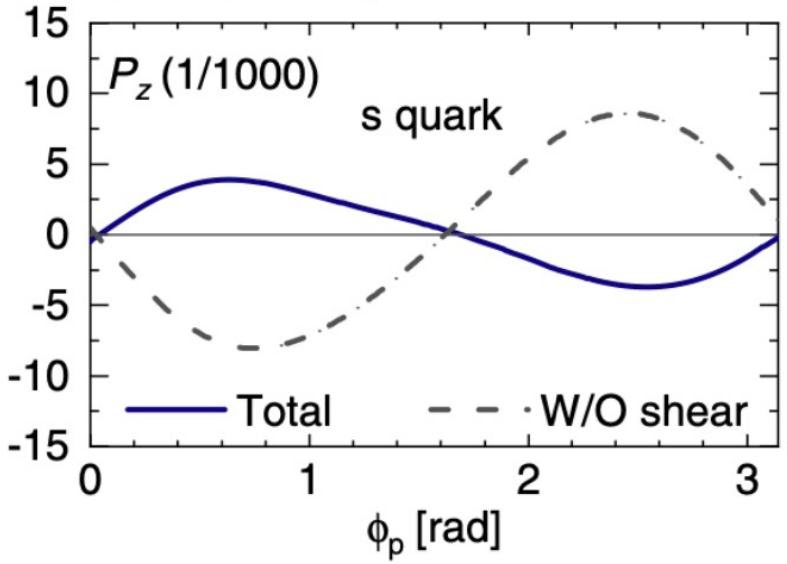
$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

Thermal shear

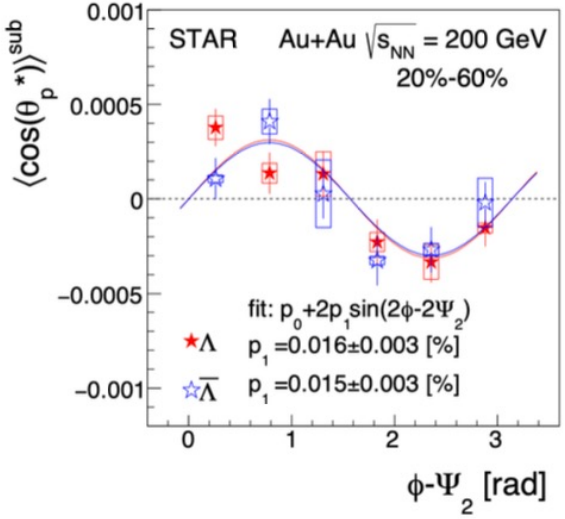
$$(\xi_{\mu\nu} = 0 \quad \text{at global equilibrium})$$

$$\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu)$$

Baochi Fu et al., PRL 127 (2021) 14, 142301
(s-quark equilibrium)



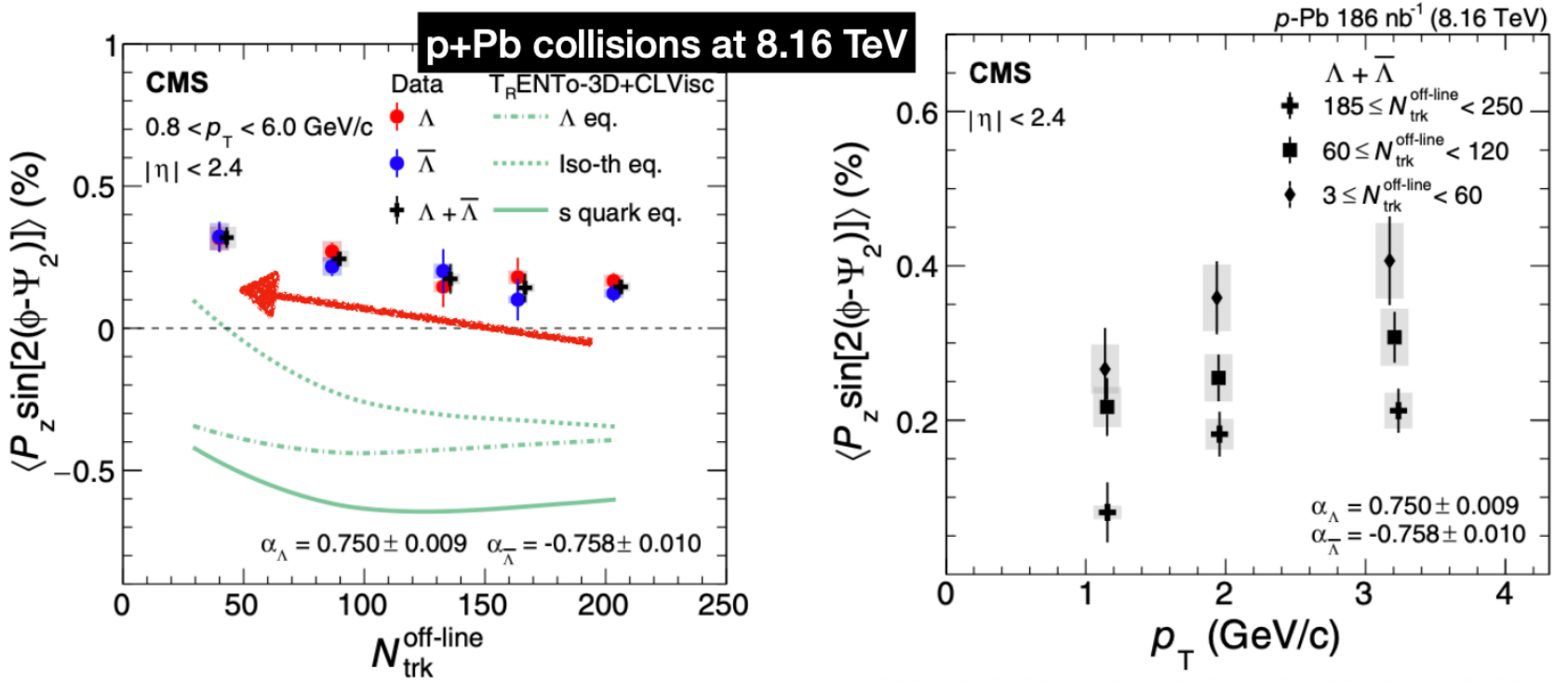
J. Adam et al. (STAR), PRL 123 (2019) 13, 132301



Longitudinal Local Polarization

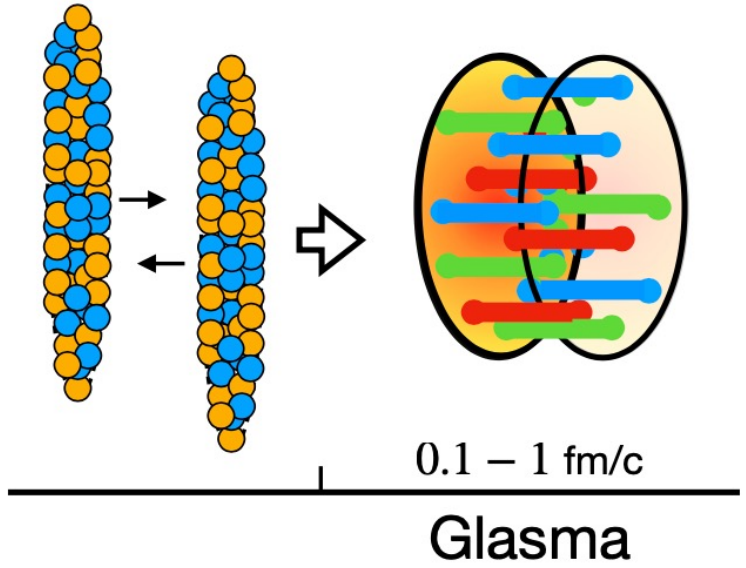
Multiplicity and p_T dependence

A. Hayrapetyan et al. (CMS), PRL. 135 (2025) 13, 132301
Cong Yi et al., *Phys.Rev.C* 111 (2025) 4, 044901 [Hydro (Vorticity+Shear)]

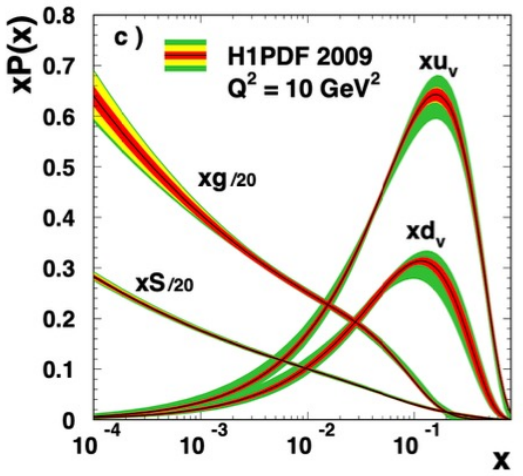


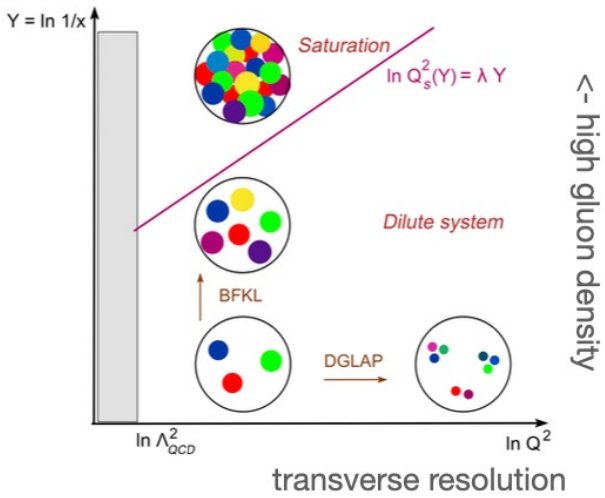
Thermal vorticity and thermal shear effect can not describe this experimental result with multiplicity and p_T dependence

Initial stages of heavy ion collisions

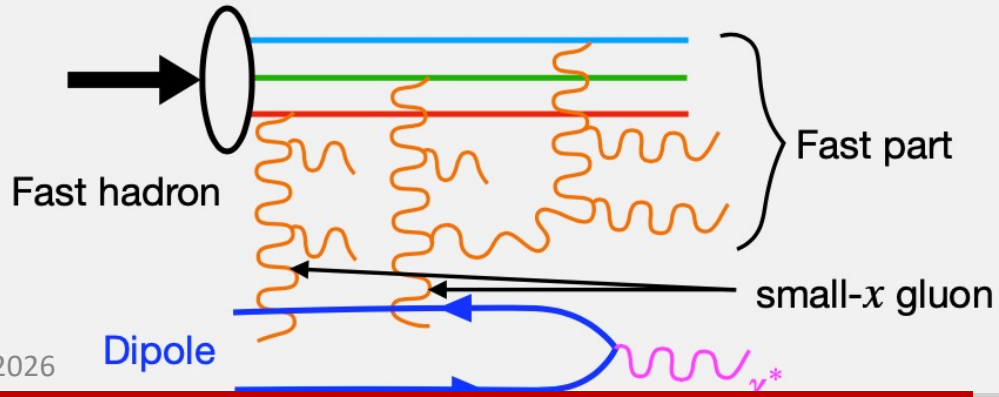


F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010





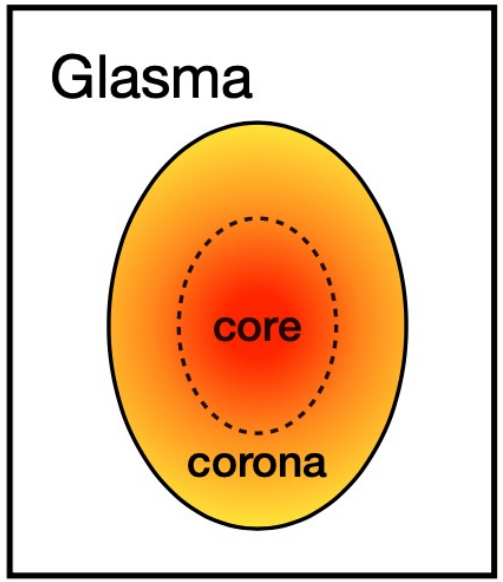
Color Glass Condensate (CGC) : Highly populated soft gluons ($E < Q_S$) sourced by hard hadrons

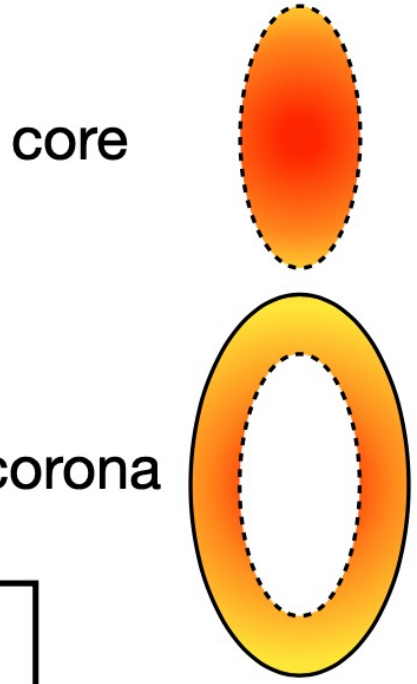


$$D^\mu F^{(a)}_{\mu\nu} = \delta^{\nu+}\delta(x^-)\rho^a(x_\perp)$$

soft gluons — hard partons

Corona effect





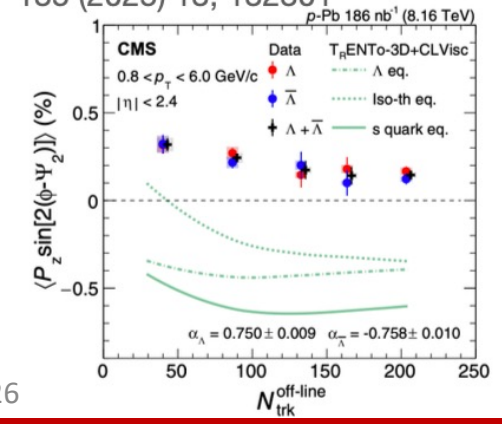
The core region undergoes full **thermalization**, forming the QGP, which then expands and hadronizes as the system cools





The corona region has a lower density and freeze-out earlier. It can hadronize directly **without passing through the QGP phase**

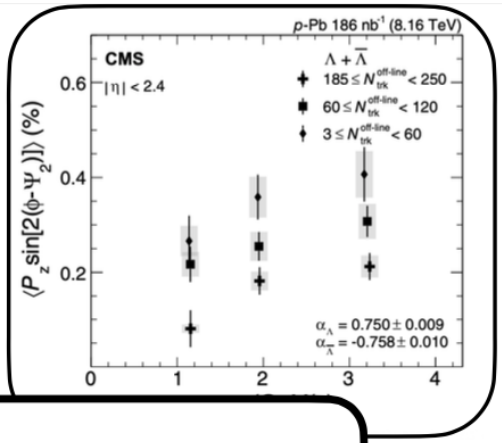
A. Hayrapetyan et al. (CMS) PRL. 135 (2025) 13, 132301

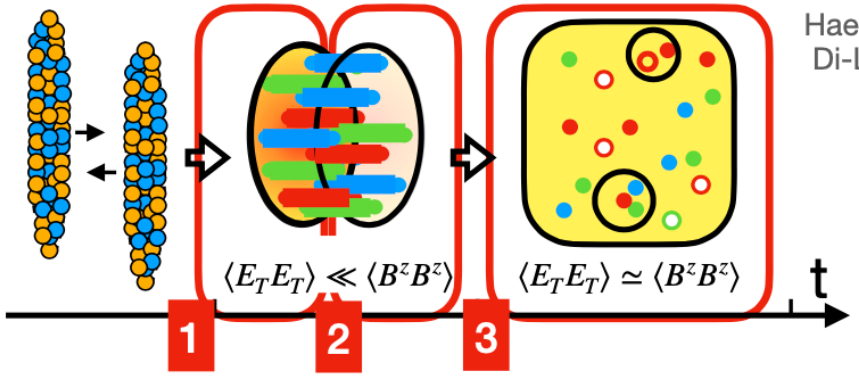


-> In small collisions system, **corona region(Glasma)** is more important

-> How the Glasma from corona can influence the local polarization of strange quarks

LSP in Glasma and QGP

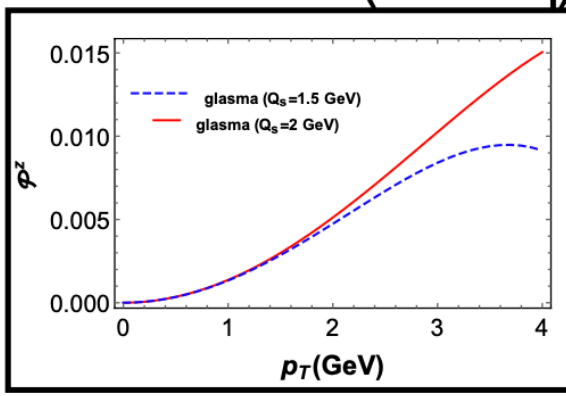




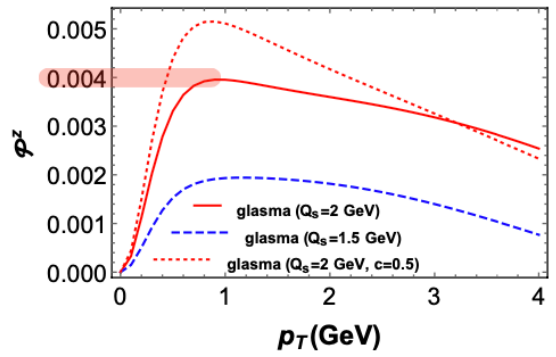
Haesom Sung, Berndt Müller, Di-Lun Yang, arXiv:2507.23210v3

$$P^z = \frac{N_{GL} P^z_{GL} + N_{QGP} P^z_{QGP}}{N_{GL} + N_{QGP}} \sim 0.1\,\%$$

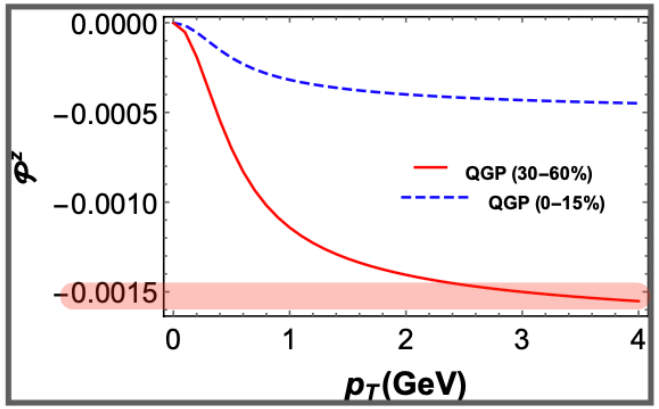
1. Glasma(non-eq)



2. Glasma(quasi-eq)



3. QGP



N_{GL} for smaller system and high p_T

N_{QGP} for larger system and low p_T

Y. Kanakubo, Y. Tachibana, and T. Hirano, Phys. Rev. C 105, 024905 (2022)

$N_{GL} \approx N_{QGP}$ where rapidity $\sim \mathcal{O}(10)$

$P^z_{GL} = 4 \times 10^{-3}$ and $P^z_{QGP} = -1.5 \times 10^{-3}$

Summary

- **In small collision systems**, initial non-equilibrium glasma (corona) generates the observed longitudinal Λ polarization with $\sin 2\phi$ pattern and an increasing tendency with p_T, which indicate that **the coherent gluons may play a significant role for local polarization.**

- To reproduce experimental data, it is essential to develop sophisticated simulations of the core and corona from the glasma to QGP.

Boosted boson jet quenching

Yang-Ting Chien

ISMD 2026, Chungli, Taiwan
August 17th, 2026

In collaboration with Paul Caucal, Yacine Mehtar-Tani



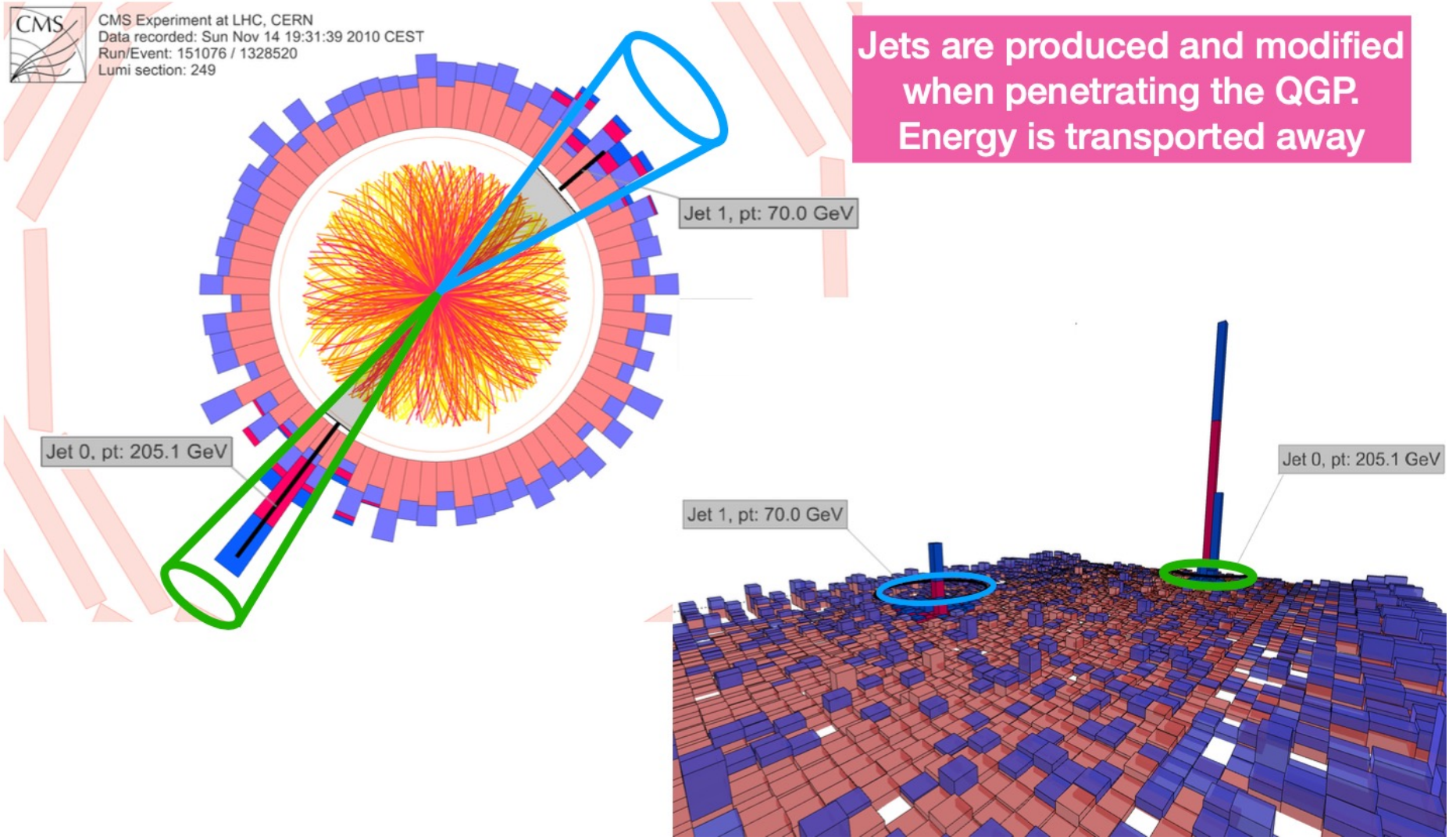




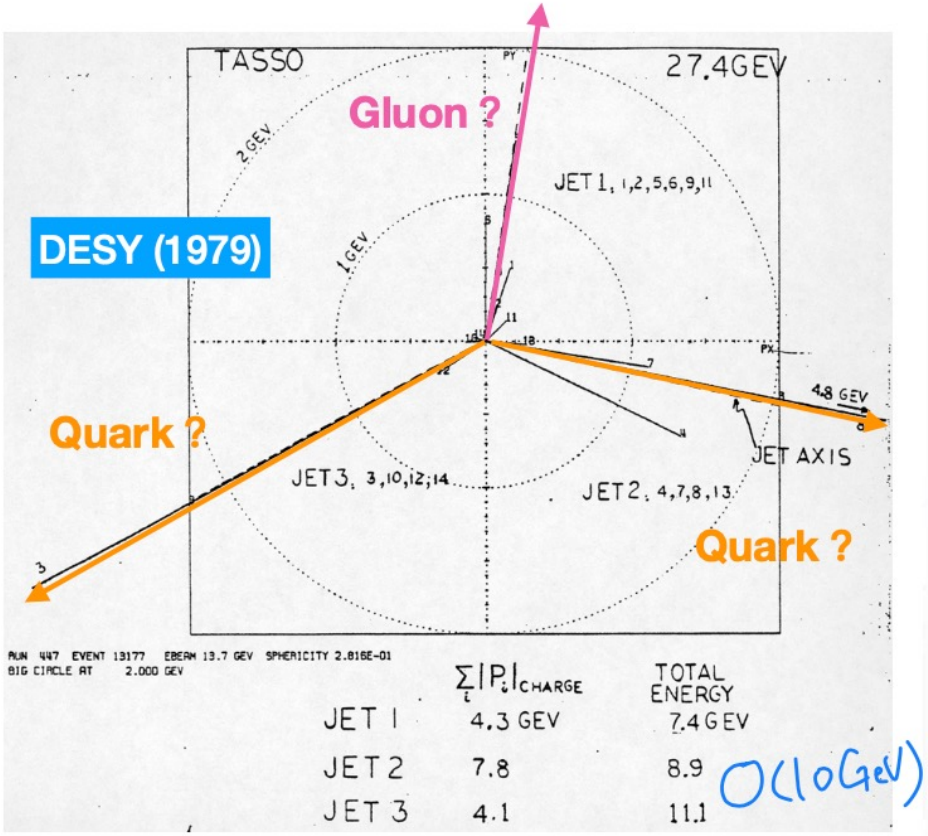
Outline

- Hard probes in heavy ion collisions
- Color coherence and decoherence
- Boosted boson jet
  - Quenching
  - Resonance modification
- Prospect at HL-LHC

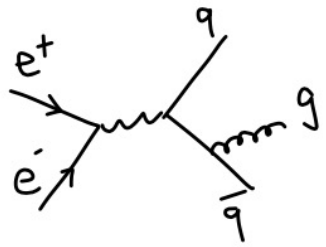
Hard probes using particle jets

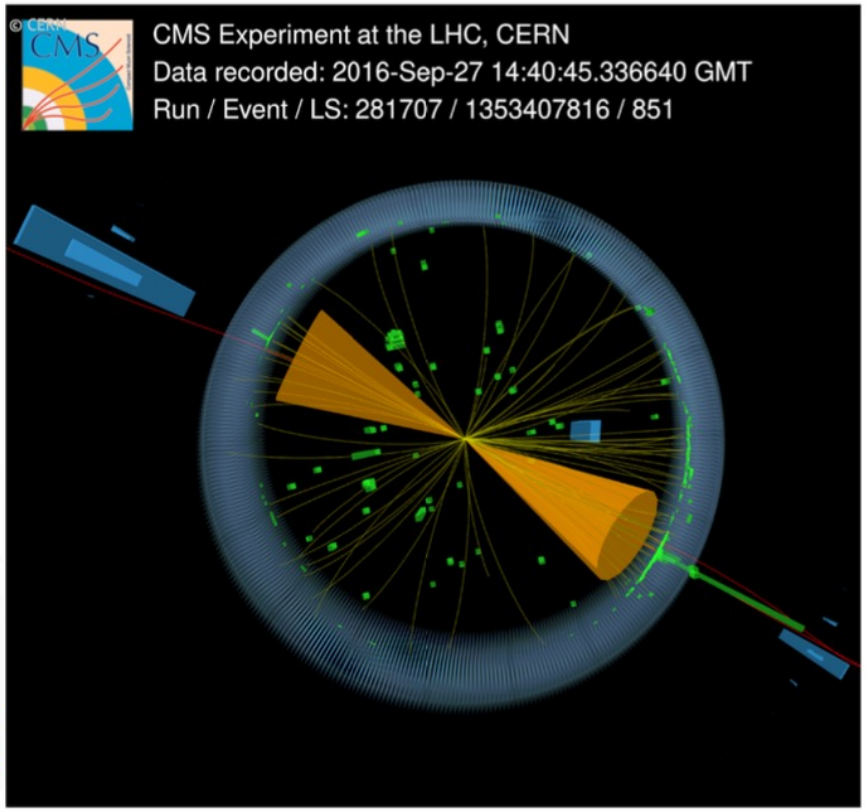


Jets are manifestation of underlying partons



3-jet event confirming the existence of gluon





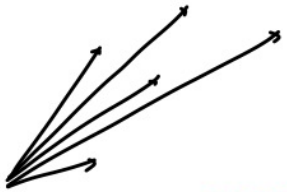
CMS-PHO-EVENTS-2021-020-1 - Small, Medium, Large, Original
This is an event with two jets (orange cones) with transverse momentum of more than 3 TeV each, produced in proton-proton collisions at a centre-of-mass energy of 13 TeV at the LHC.

O(1TeV)

across 2 orders of magnitude !

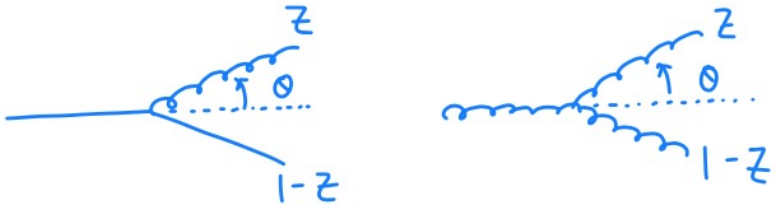
Soft and collinear emissions in jets

Jets are directional structures produced in high energy collisions: each with a bunch of collimated particles. This is a general feature of gauge theories in 3+1 D.



State of the art: 4 partons in the final state





Probability (z, θ) in the collinear limit

$$\propto \frac{\alpha_s}{2\pi} \cdot C_i \cdot P_{i \to jk}(z) \cdot \frac{1}{\theta}$$

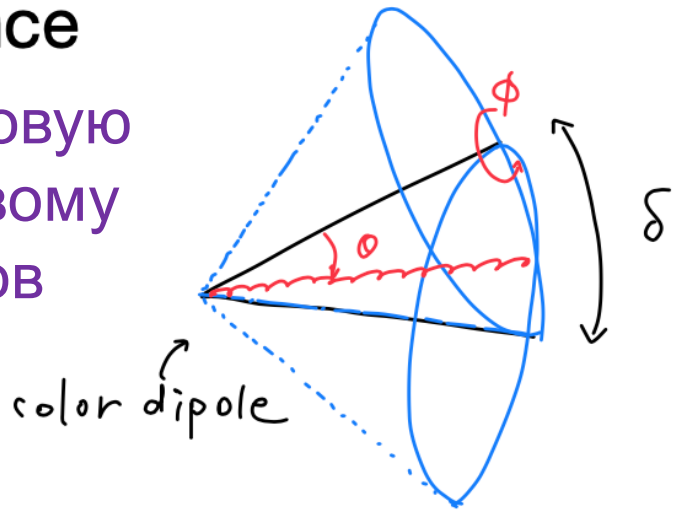
coupling strength ↑ color factor ↑ Alterelli - Parisi splitting function

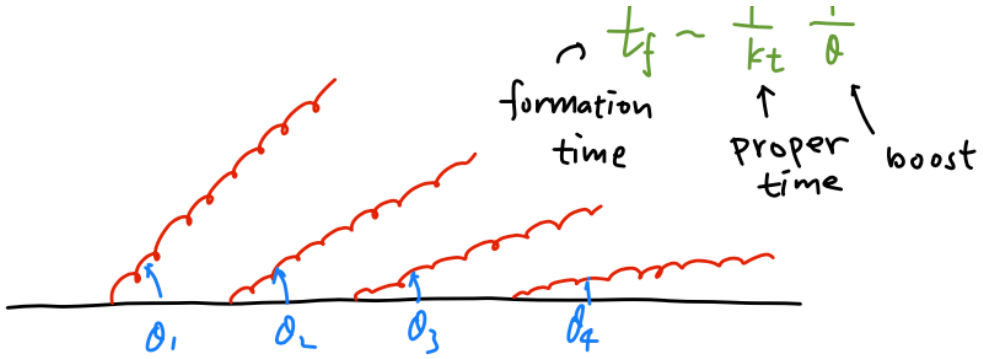
$P(z, \theta)$ becomes large when $z \to 0$ or $\theta \to 0$ (soft) (collinear)

$\propto \frac{1}{z}$ in the soft limit

Color coherence

Квантовая интерференция создает цветовую когерентность, которая приводит к угловому упорядочиванию испускаемых глюонов





$\theta_1 > \theta_2 > \theta_3 > \theta_4 > \cdots$

$\frac{1}{k_t} > t_f \cdot \delta \quad \Rightarrow \quad \boxed{\theta > \delta}$

After averaging over the azimuthal angle ϕ, the emission probability is only nonzero for $\theta < \delta$

transverse wavelength > dipole separation, then the emitted gluon can not resolve the color dipole

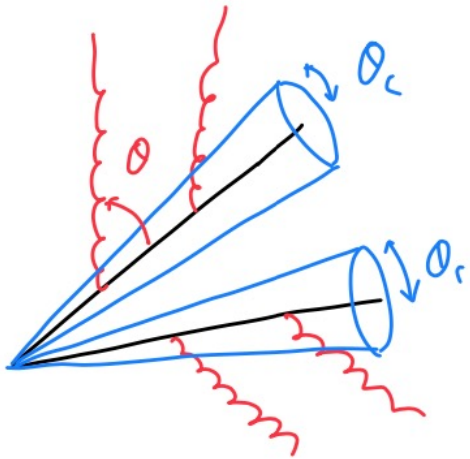
Color decoherence

As we saw, if vacuum radiation by itself can not resolve the color dipole, then color coherence will restrict the radiation to be angular ordered.

However, with the presence of the medium, the color dipole can be resolved by medium interaction with a resolution angle $\theta_c \sim \frac{1}{\sqrt{\hat{q} \cdot L^3}}$

e.g. $\hat{q}$: $1\ GeV^2/fm$ $\theta_c \approx 0.07$

L: $2\ fm$

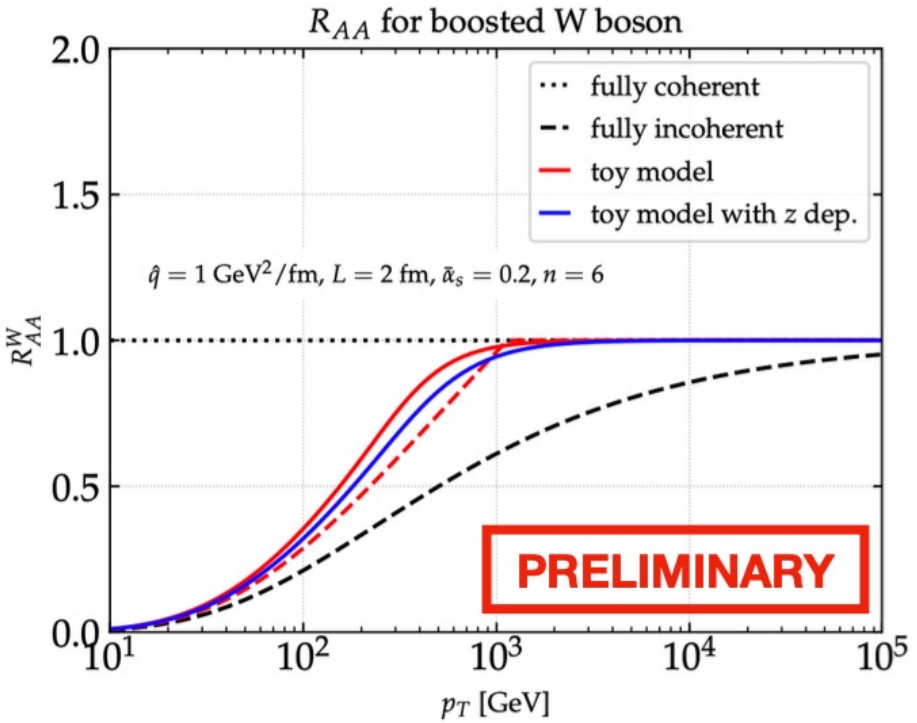


θ_c : medium resolution angle

Среда вызывает цветовое декогерентное излучение, что нарушает угловое упорядочивание

Mehtar-Tani, Salgado, Tywoniuk, Phys.Lett.B 707 (2012) 156-159

Boson jet quenching



Clear transition from decoherent (low pt) to coherent (high pt) picture for boson jet suppression

Conclusion

- Boosted boson jets are clean channels for studying color coherence and decoherence
- A boost of heavy ion data at future colliders at the energy frontiers can complete the hard probes program with all SM channels

Call for physics cases which would benefit from O(10) or more increase of heavy ion data

QCD Radiation and the Dead-Cone Effect Across Heavy-Quark Jets

Redamy Pérez-Ramos

In collaboration with Stefan Kluth and Wolfgang Ochs

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LPTHE, UMR 7589 CNRS & Sorbonne Université, Paris, France

54th International Symposium on Multiparticle Dynamics (ISMD 2026)
National Central University, Taoyuan, Taiwan: 17-21 August 2026

Outline

- **Theoretical introduction to the dead-cone phenomenon in heavy quarks jets**
- **Reconstruction of the dead-cone effect in momentum space using LEP data in charm and bottom quarks jets**
- **Comparison with pQCD within the MLLA-LPHD approach.**
- **How to identify the dead cone in top quark jets in momentum space with Pythia8 at 1 TeV in the e^+e^--annihilation**

Main references:

Stefan Kluth, Wolfgang Ochs, R. Perez-Ramos, **Phys. Rev. D 107 (2023) 094039**, **Phys. Rev. D 113 (2026) 11, 114048**

Dead cone in charm and bottom quark jets in the e^+e^--annihilation at 91.2 GeV

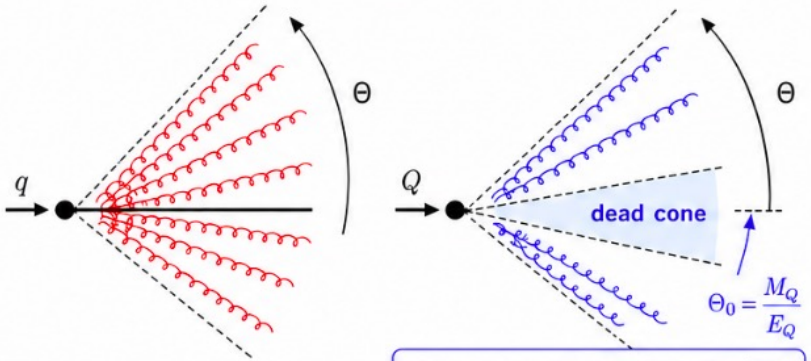
Theoretical introduction to the dead-cone phenomenon

The dead cone effect in QCD

Gluon radiation off a heavy quark is suppressed at small angles $\Theta \leq M_Q/E_Q$

1. Radiation pattern: dead cone

Light quark ($m_q \approx 0$) **Heavy quark (mass** M_Q**)**



Gluon radiation allowed down to $\Theta = Q_0/E_Q$

Suppression for $\Theta < \Theta_0 = M_Q/E_Q$

Charm and bottom hadron electroweak decays are removed for the dead cone reconstruction.

In the soft–collinear limit ($\omega \ll E_Q$):

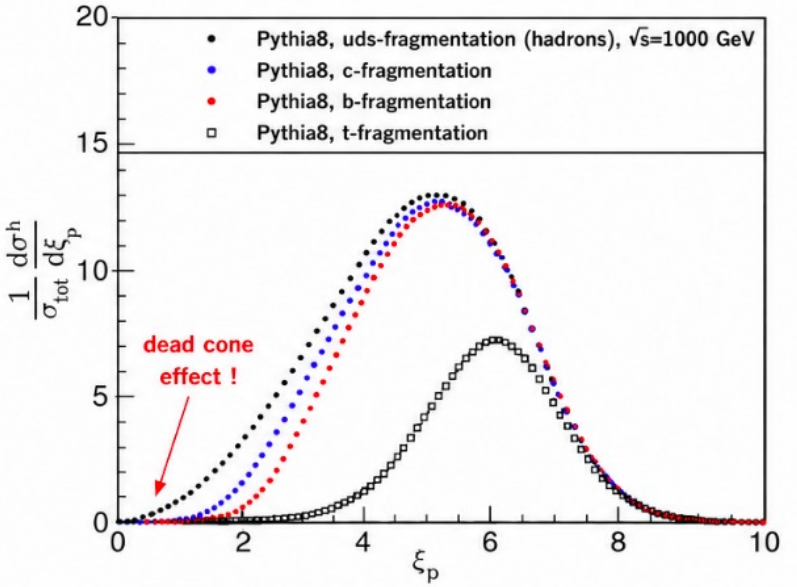
$$d\sigma_{Q\to Qg} \simeq \frac{\alpha_s}{\pi} C_F \frac{\Theta^2\, d\Theta^2}{(\Theta^2+\Theta_0^2)^2} \frac{d\omega}{\omega}, \qquad \Theta_0 = \frac{M_Q}{E_Q}$$

Consequences: suppression of particles at small angles ⇔ higher momentum (large x) in the heavy quark jet.

The effect is stronger for larger quark mass M_Q.

2. Fragmentation function in $\xi_p = \ln(1/x_p)$

Distribution of charged hadrons vs. $\xi_p = \ln(1/x_p)$



Large x (high momentum) ⟷ Small x (soft hadrons)

The heavy quark fragmentation functions are suppressed at small ξ_p (large x, *high* momentum) compared to the light quark (uds) case. The suppression is strongest for the top quark, weaker for bottom, and weakest for charm. At large ξ_p (small x), all curves converge and become similar.

MLLA evolution equations for the FF

(Modified Leading Log Approximation)

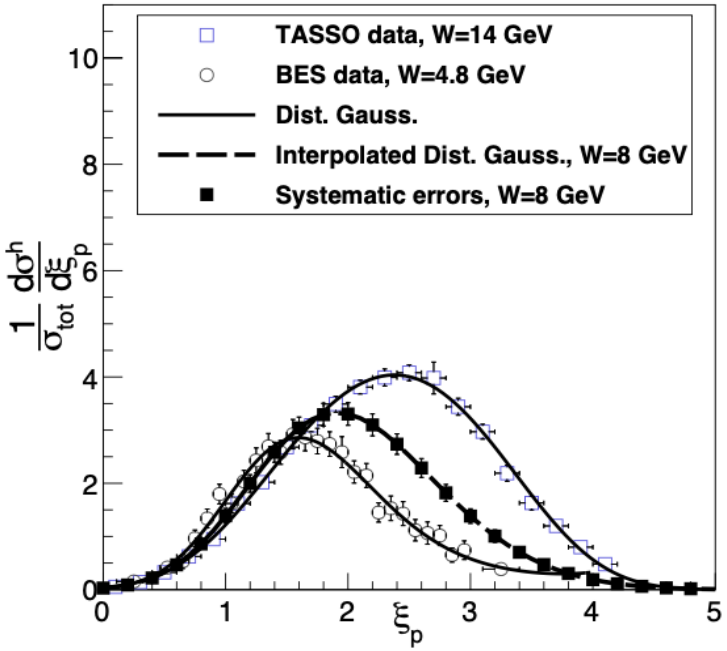
$$\underbrace{\bar{D}_q^h(\ell, y)}_{\text{quark jet}} \simeq \delta(\ell) + \frac{C_F}{N_c} \ldots \underbrace{\bar{D}_g^h(\ell', y')}_{\text{gluon jet}} \ldots \qquad \underbrace{\ell = \ln(1/x)}_{\text{infrared}} \qquad \underbrace{y = \ln(k_\perp/\Lambda)}_{\text{collinear}}$$

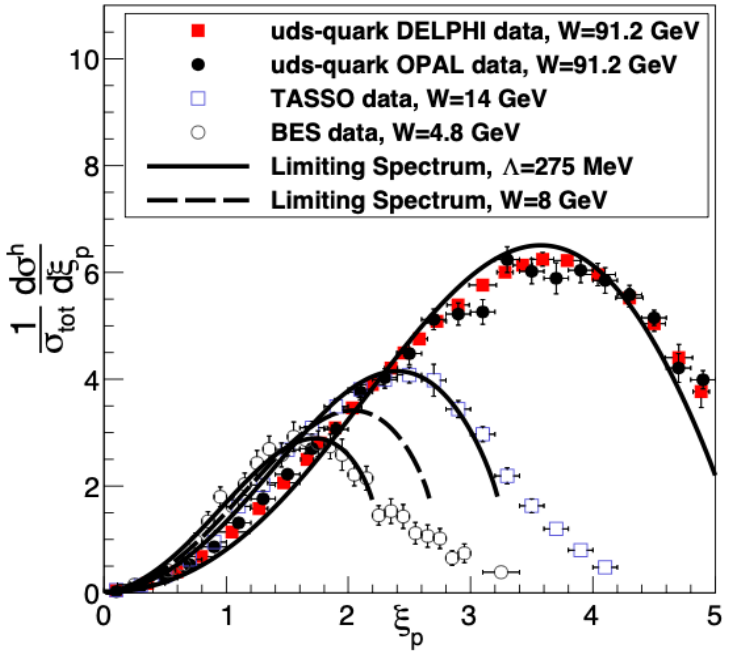
$$\underbrace{\bar{D}_g^h(\ell, y)}_{\text{gluon jet}} \simeq \delta(\ell) + \int_0^\ell d\ell' \int_0^y dy' \alpha_s(\ell' + y') \Big[1 - a_1 \delta(\ell' - \ell)\Big] \underbrace{\bar{D}_g^h(\ell', y')}_{\text{gluon jet}}$$

- DLA term: $\propto \mathcal{O}(1)$,
- hard single logs: $\propto a_1 \sim \mathcal{O}(\sqrt{\alpha_s})$ account for recoil effects,
- the dependence of α_s on two kinematical variables acount for running coupling effects.

HBP: $e^+e^-(q\bar{q})$ annihilation

Hump-backed plateau: $\tilde{D}^h_{q\bar{q}} \equiv \mathcal{K}^{ch} \times \frac{1}{\sigma}\frac{d\sigma}{d\ln(1/x_p)}$, $\mathcal{K}^{ch} \approx 1.28$ (LPHD).





$Q \gg Q_0 \sim \Lambda_{QCD} \approx 255$ MeV (limiting spectrum): this measurement shows that the partonic shower is predominant and LPHD successful!

MLLA heavy quark FFs

MLLA spectrum:

In analogy with MLLA multiplicity, the heavy quark FF can be written as the difference of the light quark FFs at $\neq$ energy scales E & $\sqrt{e}M_Q$:

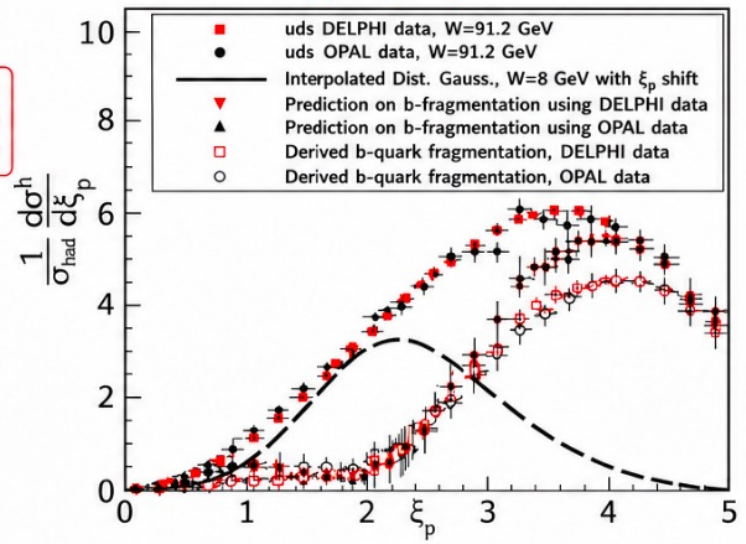
$$D_Q(x,E) = D_q(x,E) - D_q\left(\frac{x}{\langle x_Q\rangle}, \sqrt{e}\,M_Q\right).$$

- The MLLA correction factor $\sqrt{e} = 1.65$ is applied to the heavy quark mass scale M_Q of the dead cone region.
- $\langle x_Q\rangle$ (from DGLAP $D_g^g(x,W)$) is the mean momentum fraction of the primary heavy quark which reduces the light particle energies to $x < \langle x_Q\rangle$: ξ_Q-shift of the 2nd FF to the right.
- $\langle x_b\rangle = 0.7092 \pm 0.0025$ (ALEPH, DELPHI, L3, OPAL, SLD), $\langle x_c\rangle = 0.495 \pm 0.006$ (ALEPH, DELPHI, OPAL).

MLLA heavy quark FFs: comparison with data

(a) b-quark jets

Direct hadron spectra



Results:

- MLLA describes the heavy quark fragmentation functions as the difference of light quark FFs at two scales, including the ξ_Q-shift and the MLLA correction factor $\sqrt{e} = 1.65$.
- The reduced phase space for gluon radiation off a heavy quark — implemented through the subtraction of the low-energy term $\sqrt{e}\,M_Q$ — suppresses particle production at small angles, leading to a softer fragmentation of heavy quarks.
- The agreement confirms the universality of the MLLA description of heavy quark fragmentation across different jet flavors (uds, c and b) and experiments.

Physical picture:

The dead cone effect inhibits gluon radiation at small angles ($\theta < \theta_m = M_Q/E$). The suppression mainly arises from the subtraction of the low-energy term $\sqrt{e}\,M_Q$ (reflecting the heavy quark mass) in the MLLA spectrum, which reduces the phase space for soft gluon emission and yields a suppression of hadron production at low ξ_p.

Bottom > Charm > uds

Эффект «мертвого конуса» подавляет излучение глюонов под малыми углами. Подавление в основном возникает из-за вычитания низкоэнергетического члена $\sqrt{e}M_Q$ из спектра MLLA, что уменьшает фазовое пространство для излучения мягких глюонов и приводит к подавлению образования адронов при низких значениях.

Conclusions

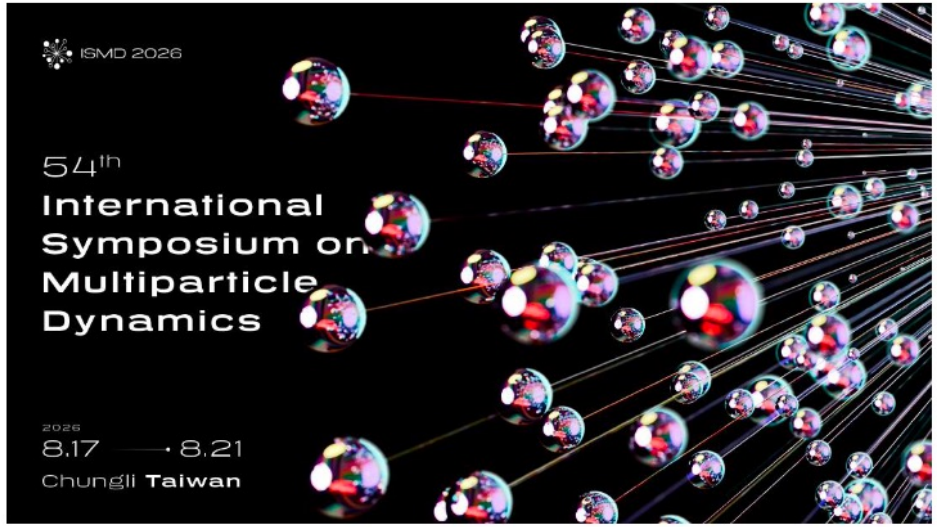
- The dead cone effect is reconstructed directly from heavy-quark fragmentation functions in momentum space.
- The suppression of energetic hadrons increases with the quark mass,

$$\boxed{\text{uds} > c > b > t}$$

  providing a unified picture of heavy-quark fragmentation.
- The measured b- and c-quark spectra are quantitatively described by the MLLA prediction, confirming the perturbative QCD origin of the dead cone.
- The same MLLA framework naturally extends to top-quark jets after separating production and decay radiation, opening a new precision test of QCD at future colliders.

Heavy-quark frag. from charm to top follows a universal MLLA/QCD picture: the dead cone suppresses gluon radiation, yielding progressively softer frag. as $M_Q \nearrow$

Charmed meson production by recombination in relativistic heavy ion collisions



August 17th, 2026
National Central University, Taiwan

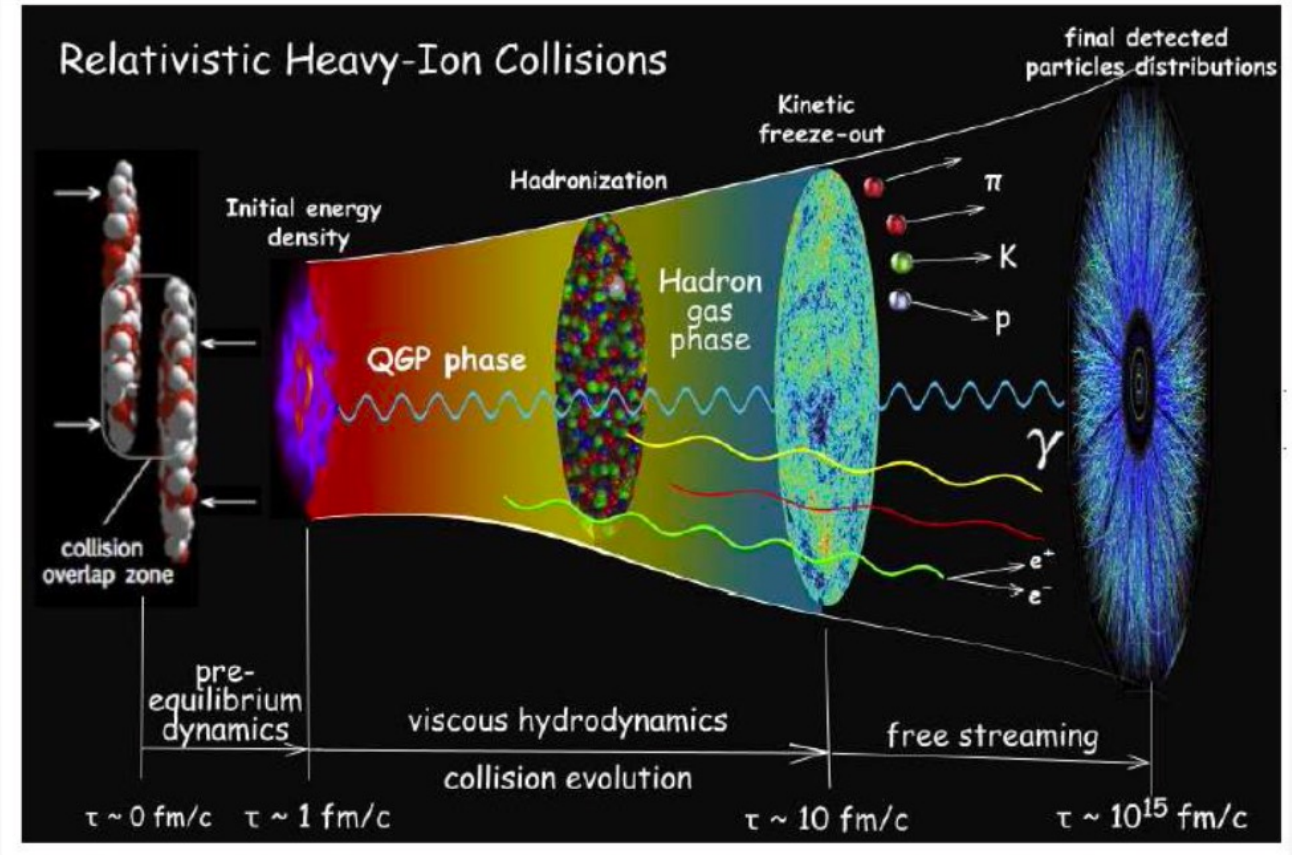
Sungtae Cho
Kangwon National University

in collaboration with Prof. Su Houng Lee,
arXiv:2510.18673, work in progress

Изучен выход очарованных и странных мезонов (Ds, Ds∗, Ds∗0(2317) и Ds1(2460), фокусируясь на их образовании путем коалесценции из КГП в HIC при $\sqrt{s_{NN}}$ = 5,02 ТэВ. Рассчитаны распределения по поперечному импульсу и выходы Ds, Ds∗, Ds∗0(2317) и Ds1(2460) мезонов на основе модели коалесценции. Обнаружено: выход и распределение по p_t D_s-мезона хорошо согласуются с экспериментальными измерениями. Исследовано отношение поперечного импульса между D_s- и D^0-мезонами и роль легких и странных кварков в образовании очарованных мезонов в столкновениях тяжелых ионов. Рассчитано распределение по p_t и выход D_s^{*0}(2317)-мезона в 4-q состоянии, выполнено сравнение с аналогичными показателями D_s^{*0}(2317)-мезона в 2-q состоянии.

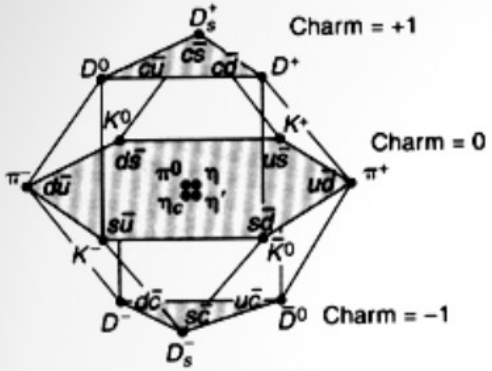
Introduction

– Relativistic heavy ion collisions



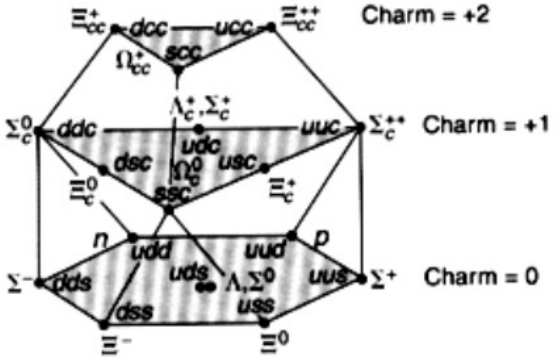
U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– Production of charmed hadrons



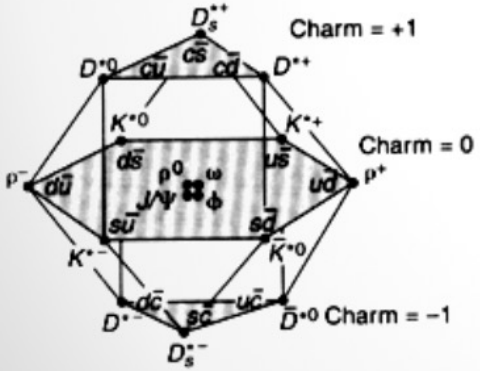
0⁻ Mesons

(a)



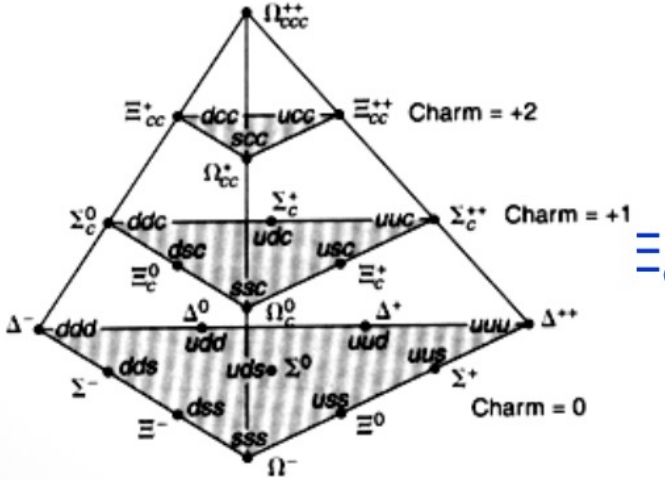
$\frac{1^+}{2}$ Baryons

(c)



1⁻ Mesons

(b)



$\frac{3^+}{2}$ Baryons

(d)

1) Charmed mesons:
D, D*, D_s, D_s*
D_{s0}*(2317), D_{s1}(2460)
D_{s1}(2536), D_{s2}*(2573)

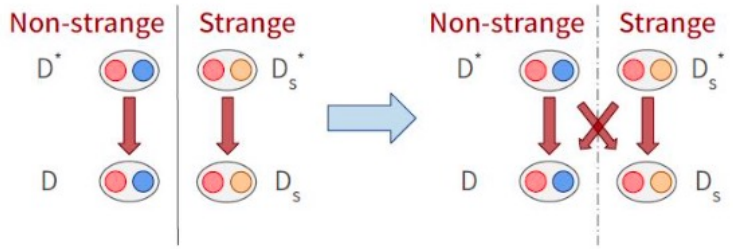
2) Singly charmed baryons: Λ_c(2286), Λ_c(2595), Λ_c(2625), Σ_c(2455), Σ_c(2520), Ξ_c(2470), Ξ_c(2578), Ξ_c(2645), Ω_c(2695), Ω_c(2770)

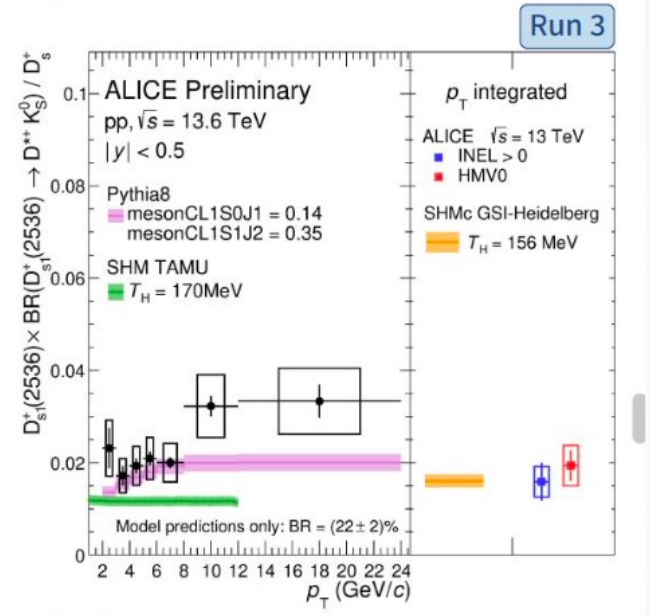
$$N_C = \sum_i N_i \qquad \omega = \frac{1}{\mu\sigma^2}$$

– Measurements of $D_{s1}(2536)$, $D_{s2}^*(2573)$

Orbitally excited D_s mesons

- Could **orbitally excited charm states** play a role?
- $D_{s1}^{*+}(2536) \rightarrow D^{*+}K^0_S$, $D_{s2}^{*+}(2573) \rightarrow D^+K^0_S$
  - Strange excited states decaying to non-strange ground state
- Inclusion of these states in model prediction can effectively **"dilute" the D_s^+/D^+ ratio**
  - Could flatten models where excited strange D mesons only decay to D_s^+ mesons



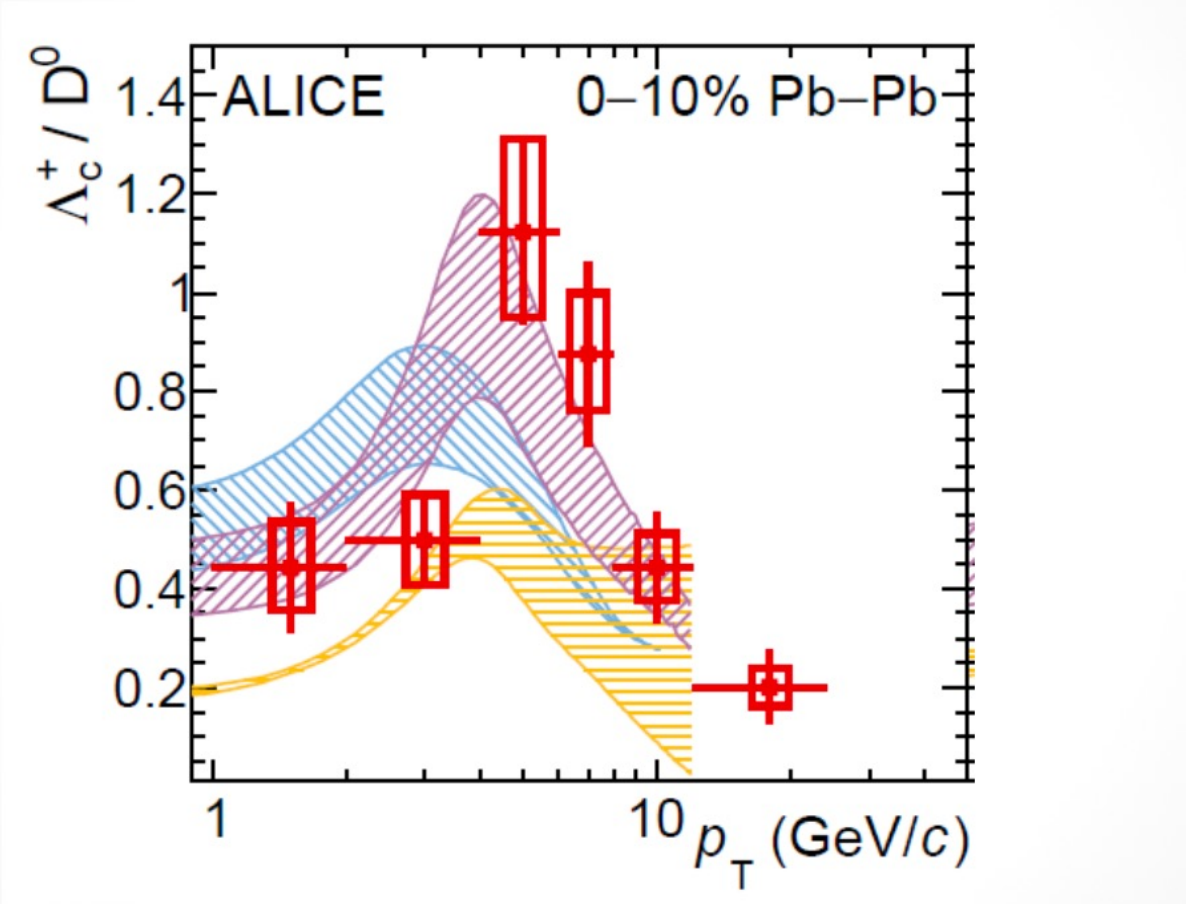


CR-BLC JHEP 08 (2015) 003
TAMU Phys.Lett.B 795 (2019) 117-121
GSI-Heidelberg JHEP 07 (2021) 035

Fabrizio Chinu | Strangeness in Quark Matter 2026, Los Angeles | 19/20

F. Chinu on behalf of ALICE Collaboration, Strangeness in Qaurk Matter 2026

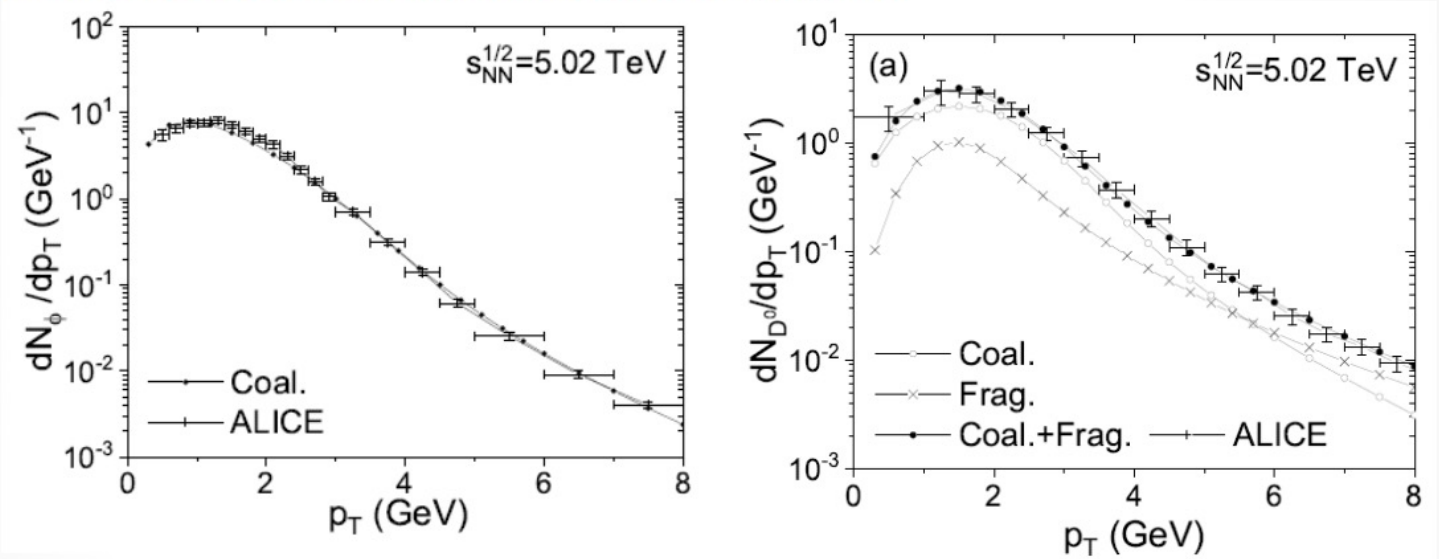
– Measurements of Λ_c/D_0 ratios at LHC



S. Acharya et al, (ALICE Collaboration), Phys. Lett. **B** 839, 137796 (2023)

– Transverse momentum distributions of charm quarks at 5.02 TeV

S. Cho and S. H. Lee, arXiv:2510.18673, work in progress



S. Acharya et al. (ALICE Collaboration),JHEP **01**, 174 (2022)

$$\frac{dN_q}{d\vec{p}_{qT}} = \begin{cases} \frac{V}{(2\pi)^3} m_T e^{-m_T/T_{eff}}, & p_{qT} \leq 1.50 \text{ GeV} \\ 21.95\ (\text{GeV}^{-2}) e^{-0.17(p_{qT}/p_{0T})^{3.23}} & \\ + \frac{80112\ (\text{GeV}^{-2})}{(1.0+(p_{qT}/p_{0T})^{0.65})^{10.29}}, & p_{qT} > 1.50 \text{ GeV} \end{cases}$$

$$\frac{d^2N_c}{d^2\vec{p}_{cT}} = \begin{cases} 1.63\ (\text{GeV}^{-2}) e^{-0.29(p_{cT}/p_{0T})^{2.03}}, & p_{cT} \leq 1.80 \text{ GeV} \\ 7.95\ (\text{GeV}^{-2}) e^{-3.49(p_{cT}/p_{0T})^{3.59}} + \frac{90112\ (\text{GeV}^{-2})}{(1.0+(p_{cT}/p_{0T})^{0.50})^{14.19}}. & p_{cT} > 1.80 \text{ GeV} \end{cases}$$

$$dN_c/dy = 16.7.$$

Conclusions

– Charmed meson production by recombination in relativistic heavy ion collisions

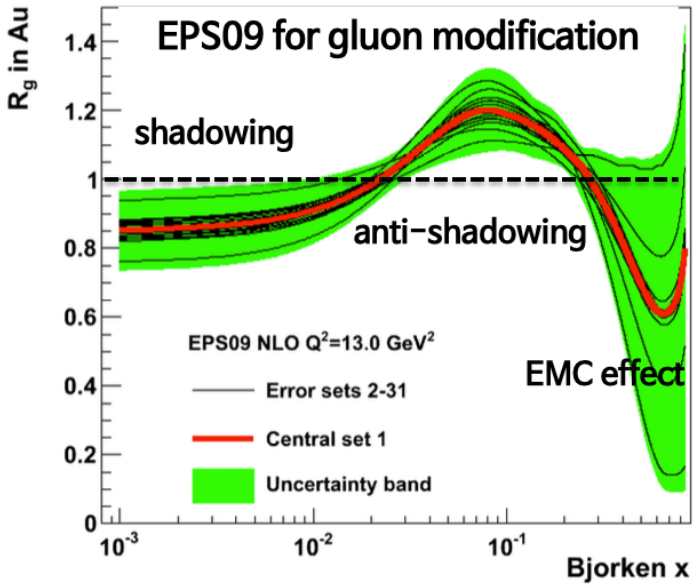
1) Studying the production of charmed mesons can help us understand in more detail the hadron production mechanism as well as the strangeness enhancement in heavy ion collisions
2) It is essential to consider the production of D_s^*, $D_{s0}^*(2317)$, $D_{s1}(2460)$ $D_{s1}(2536)$ and $D_{s2}^*(2573)$ mesons in order to understand the yield or transverse momentum distribution of D and D_s mesons
3) Many more studies are expected; stay tuned for new results soon

Multiplicity-Dependent Charmonium Production in Small Collision Systems with PHENIX

Sanghoon Lim
for the PHENIX collaboration
Yonsei University



Various effects on charmonia production in small systems

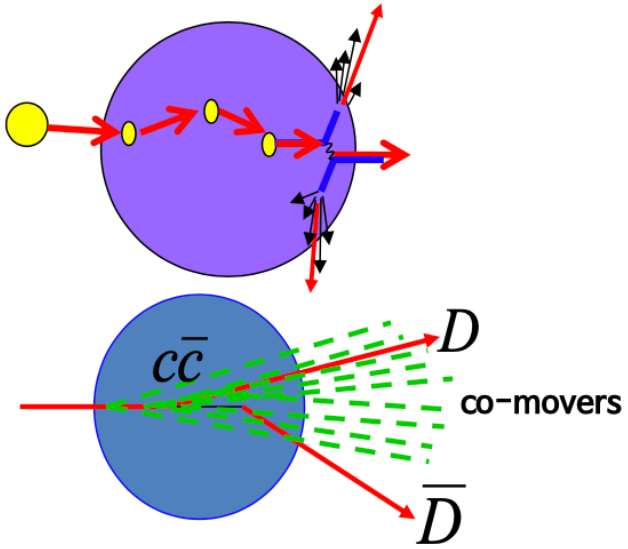


Modified parton distribution functions in nuclei compared to those in the nucleon



Scattering with nuclear matter:
(Initial-state and/or final-state interaction)

- Transverse momentum broadening
- Energy loss
- Break-up of bound states

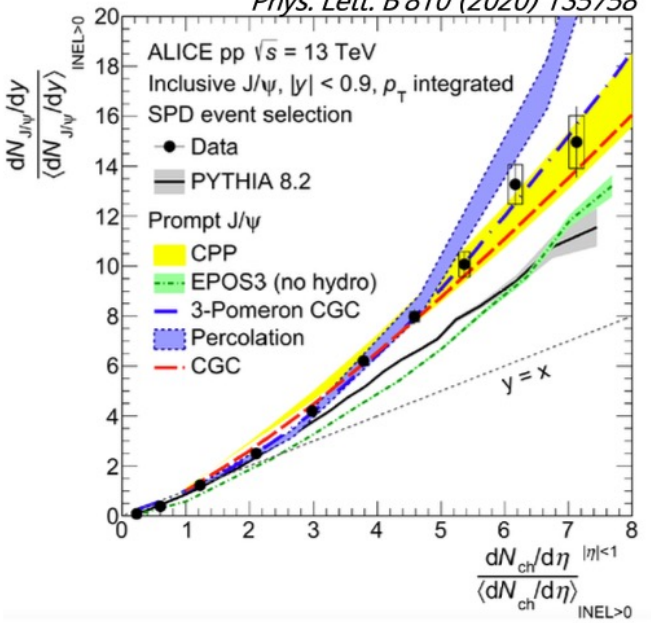


2

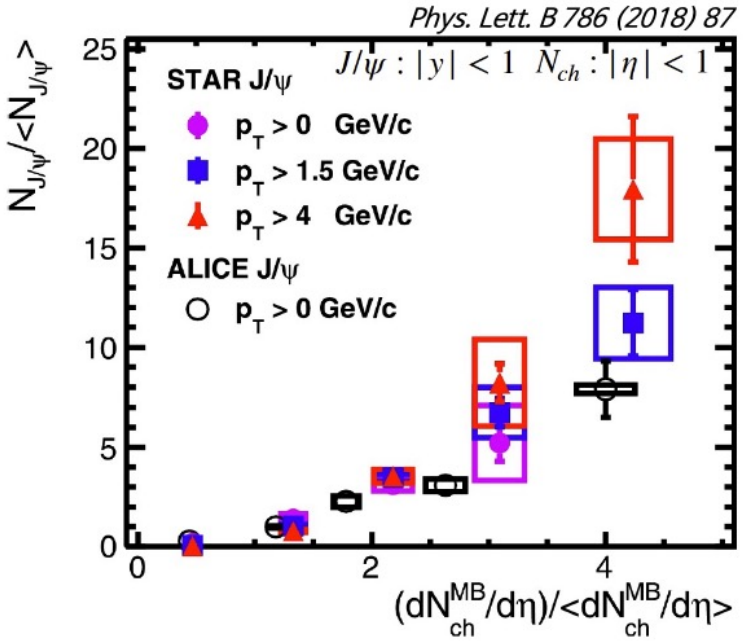
R_g - the ratio of gluon PDF (nPDF) in a nucleus to that in a free nucleon at a given longitudinal momentum fraction x. Nuclear effects: shadowing ($R_g < 1$), antishadowing ($R_g > 1$), and g- saturation—at RHIC and LHC.

Various effects on charmonia production in small systems

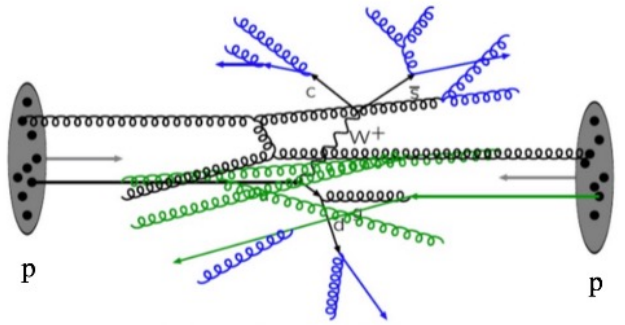
Phys. Lett. B 810 (2020) 135758



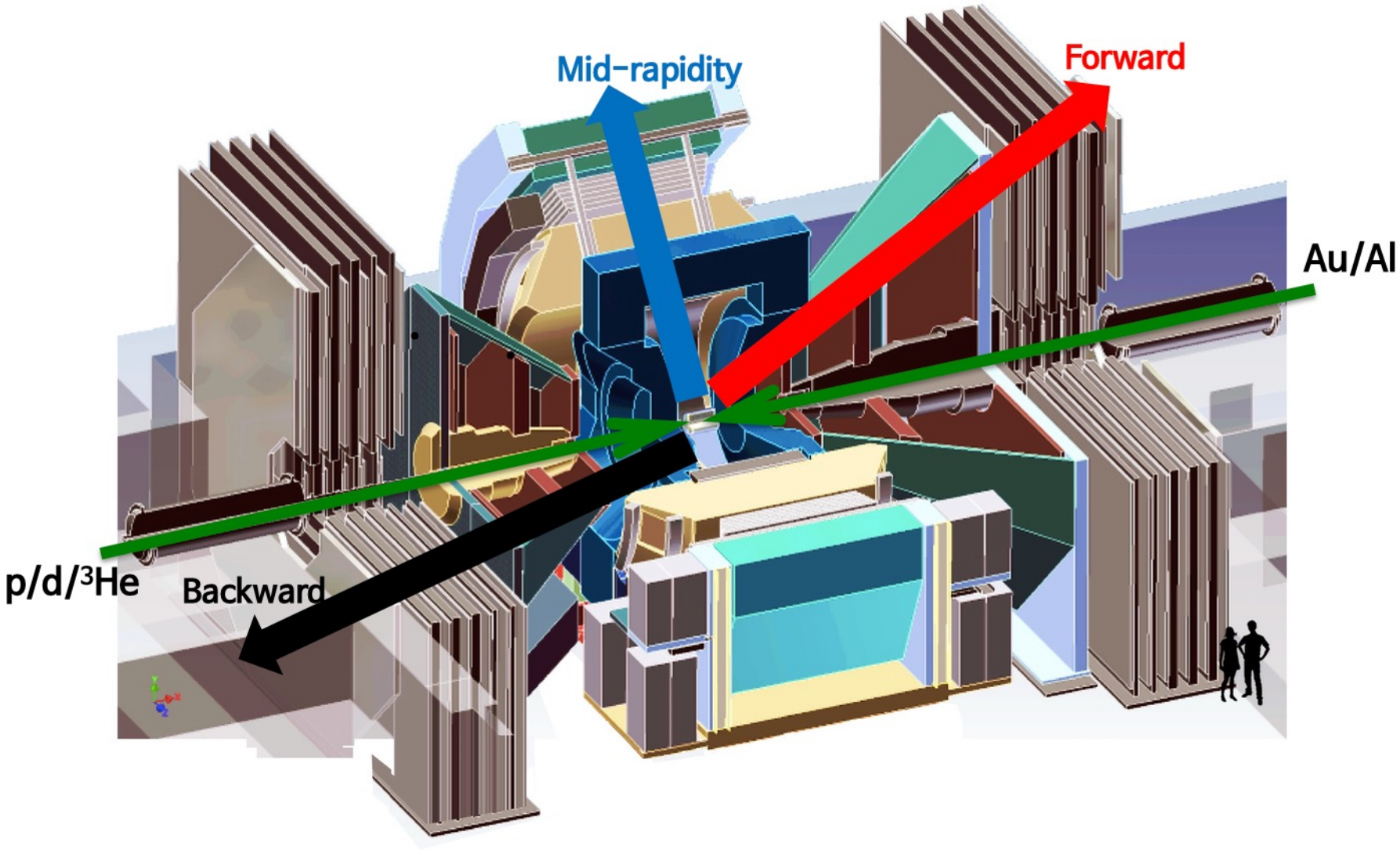
Phys. Lett. B 786 (2018) 87



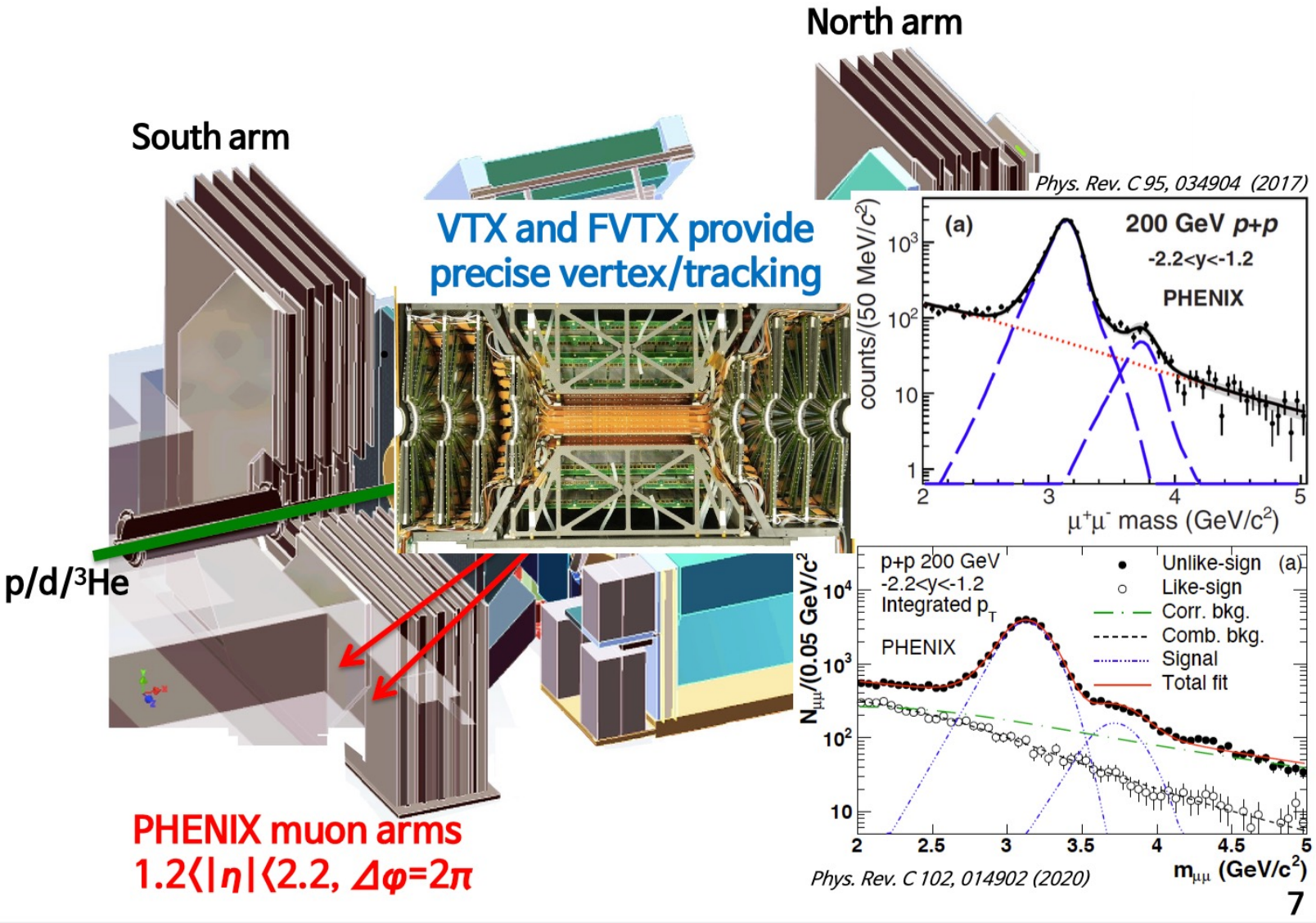
- Inclusive J/ψ yield increases with particle multiplicity in p+p collisions at 13 TeV and 200 GeV
  - Similar multiplicity dependence at two energies
  - Multiparton interaction is important for J/ψ production in both energies



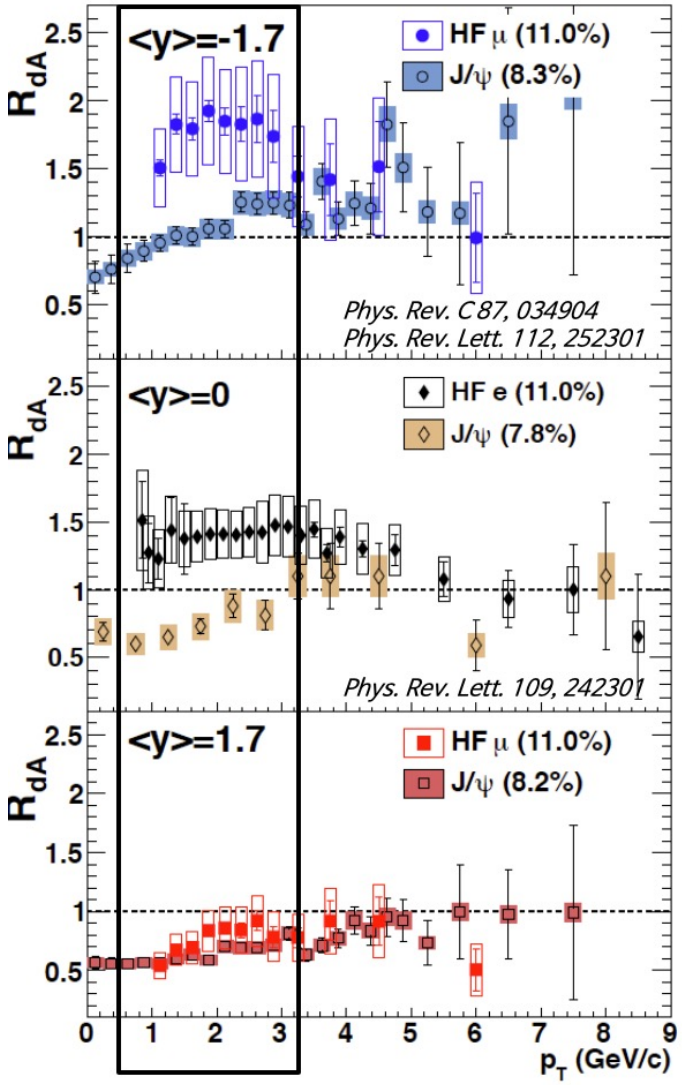
Charmonia measurements at PHENIX



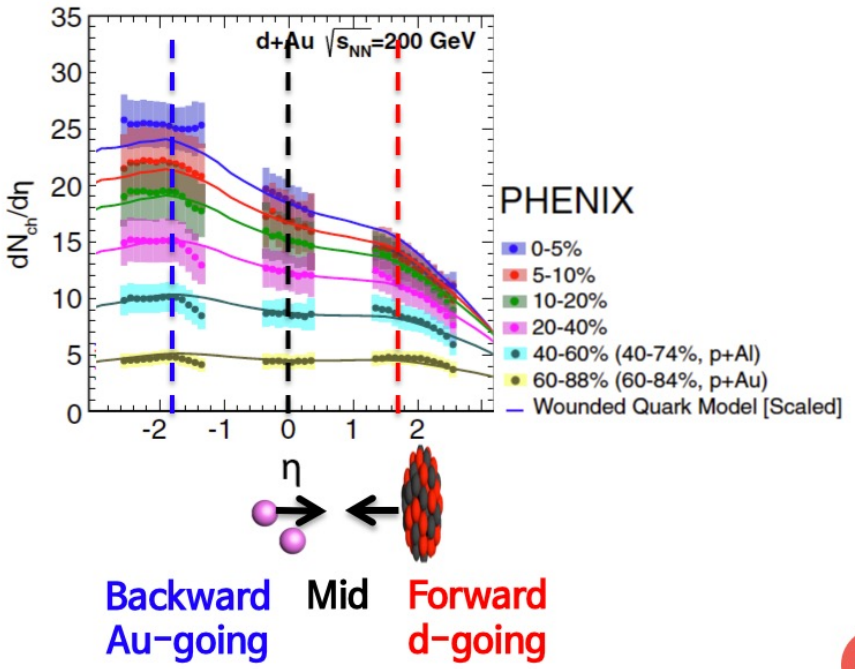
Charmonia measurements at PHENIX



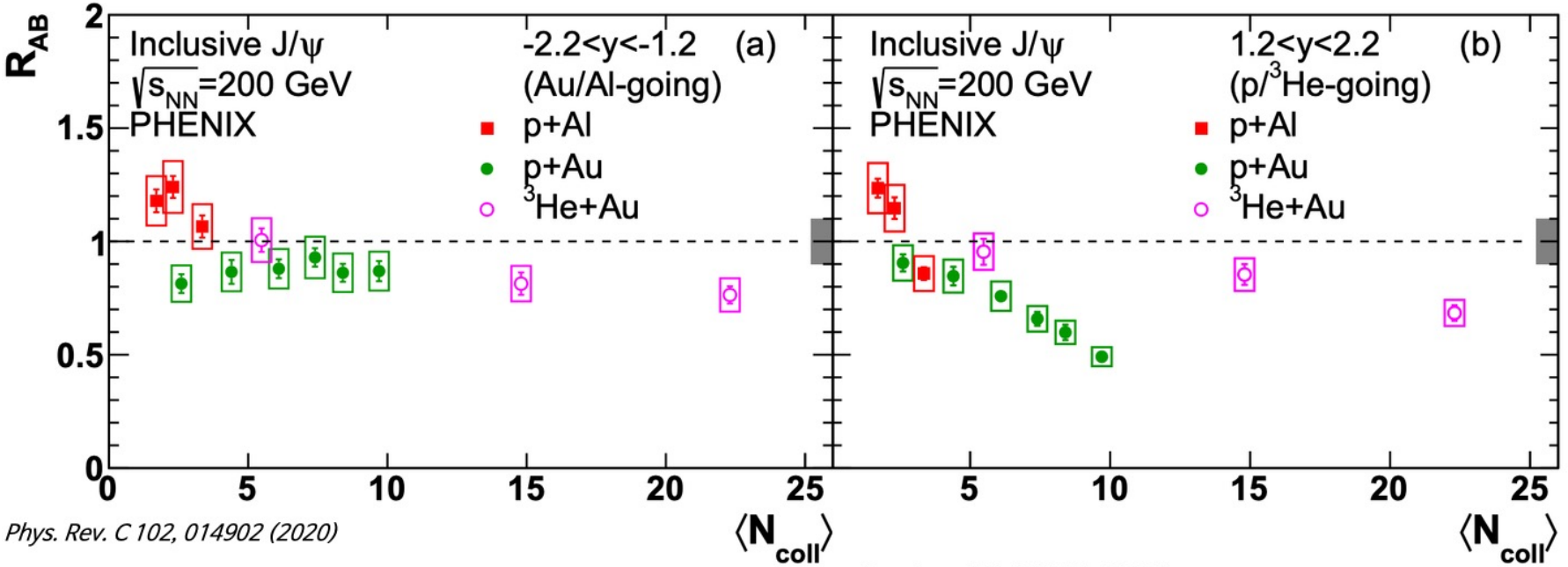
Final-state effects in small systems: HF muon and J/ψ



- In central (0-20%) d+Au collisions
  - Similar nuclear modifications between HF muon and J/ψ at forward rapidity
  - HF muon yield is enhanced in $1 \langle p_T \langle 5$ GeV/c but J/ψ yield is suppressed at mid- and backward rapidity

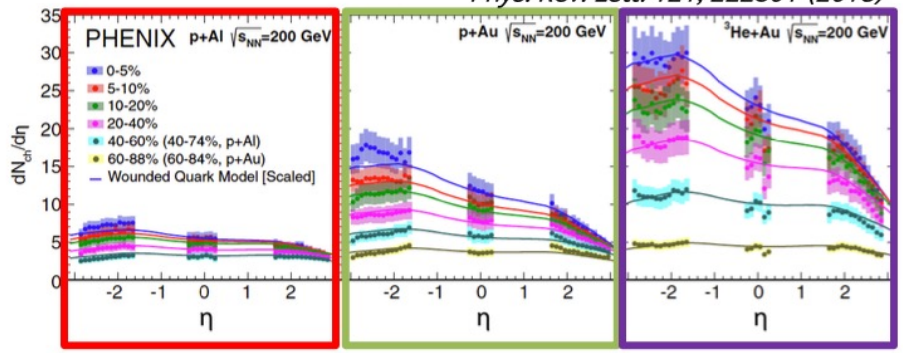


Final-state effects in small systems: J/ψ



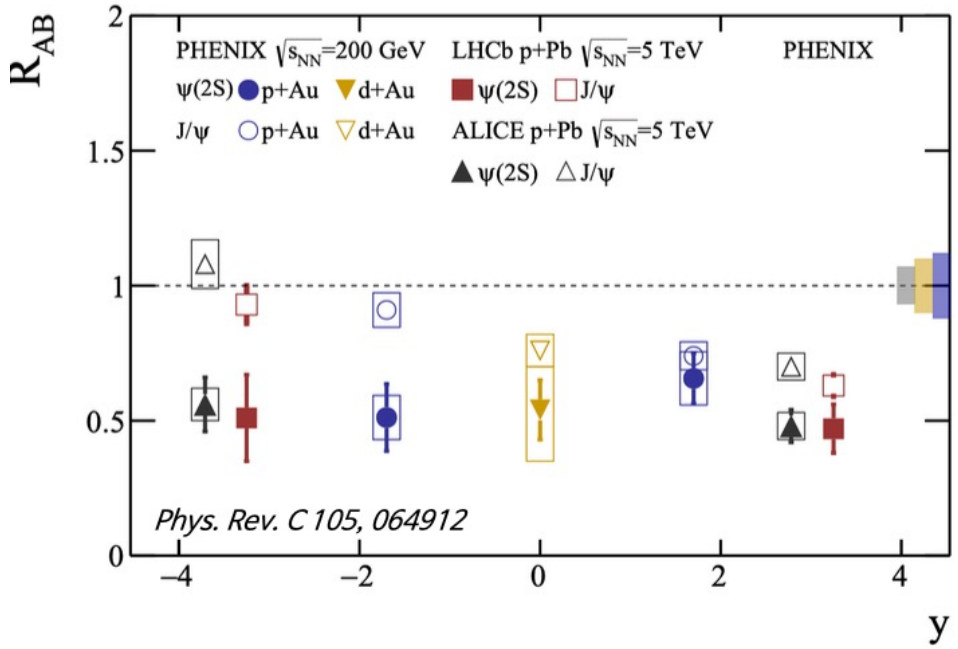
Phys. Rev. C 102, 014902 (2020)

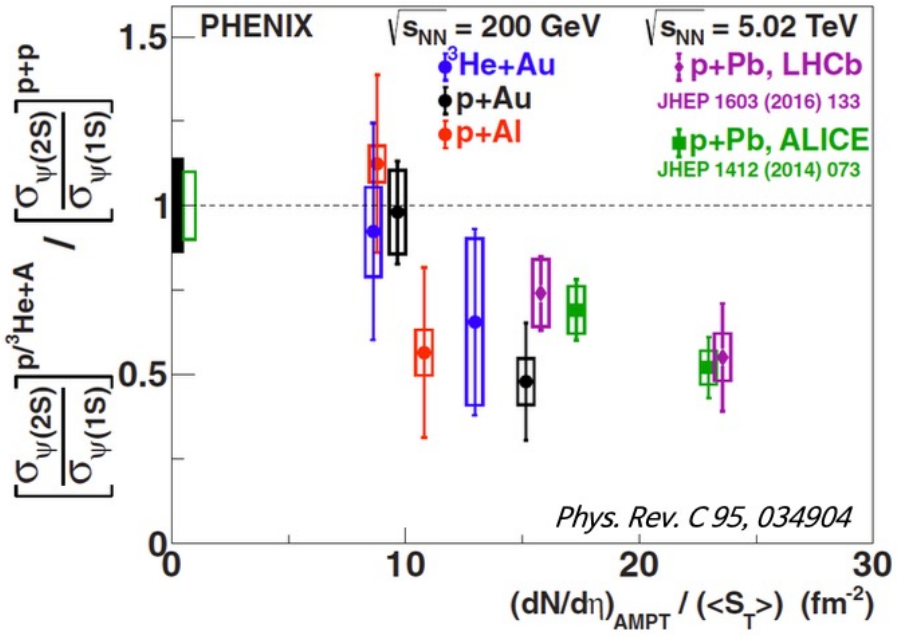
Phys. Rev. Lett. 121, 222301 (2018)



- No strong centrality dependence at backward rapidity, whereas a clear centrality dependence at forward rapidity

Final-state effects in small systems: J/ψ and ψ(2S)

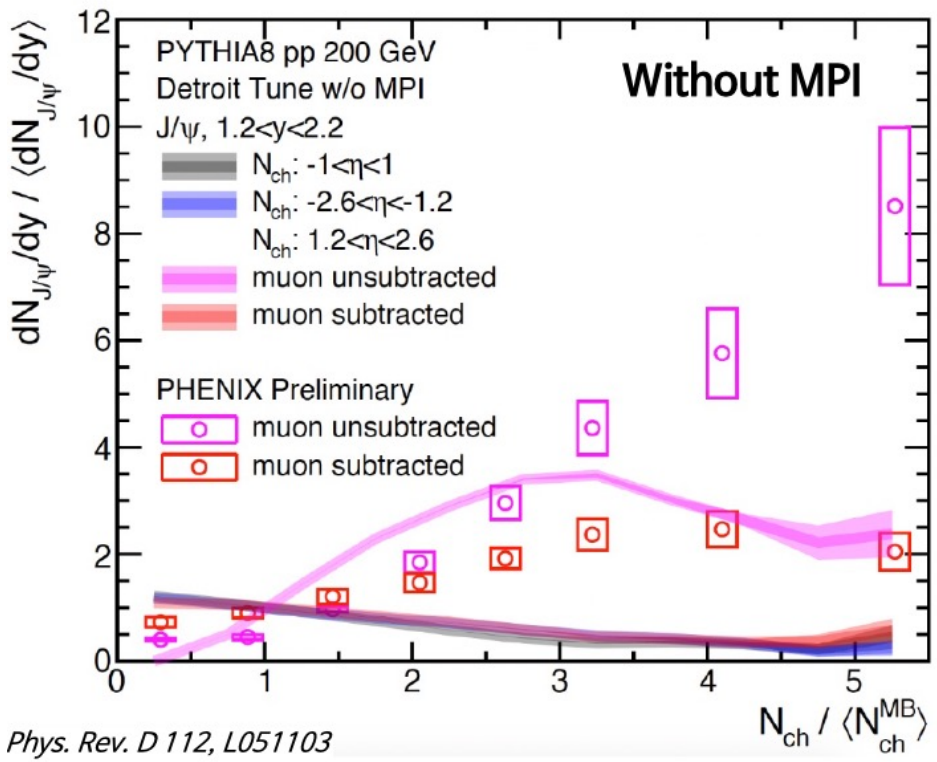


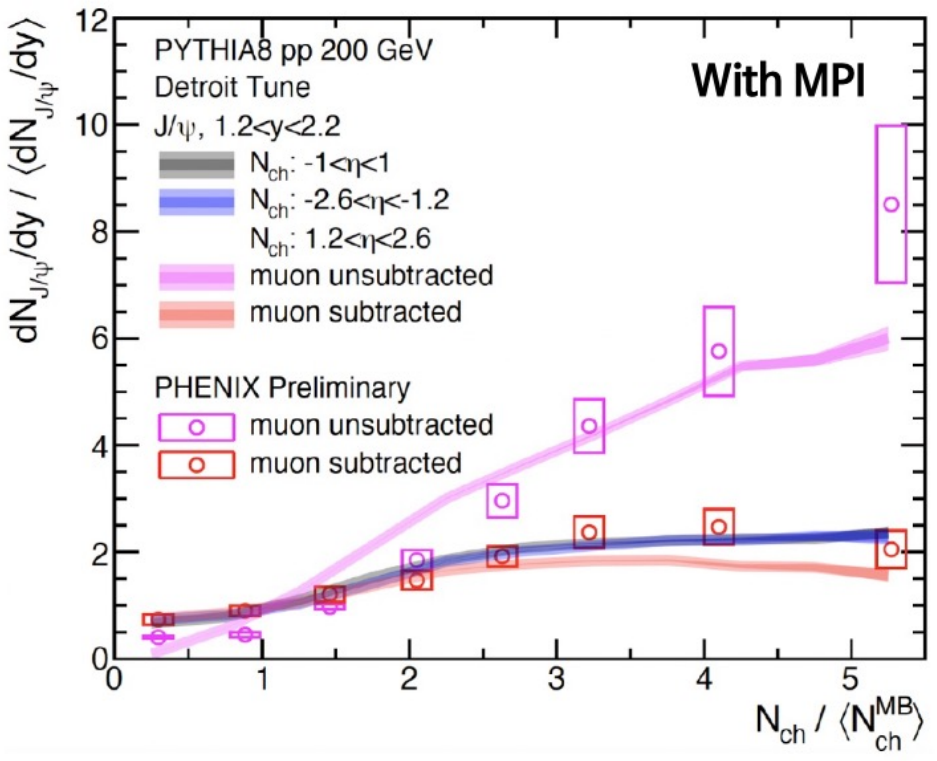


- Stronger suppression of ψ(2S) at backward rapidity (A-going direction)
  - The co-mover disassociation model describes the rapidity dependence in p+Au collisions but little difference in p+Al collisions

- Relative ψ(2S) suppression increases as the co-moving particle density increases

Multiplicity-dependent J/ψ yields in p+p collisions

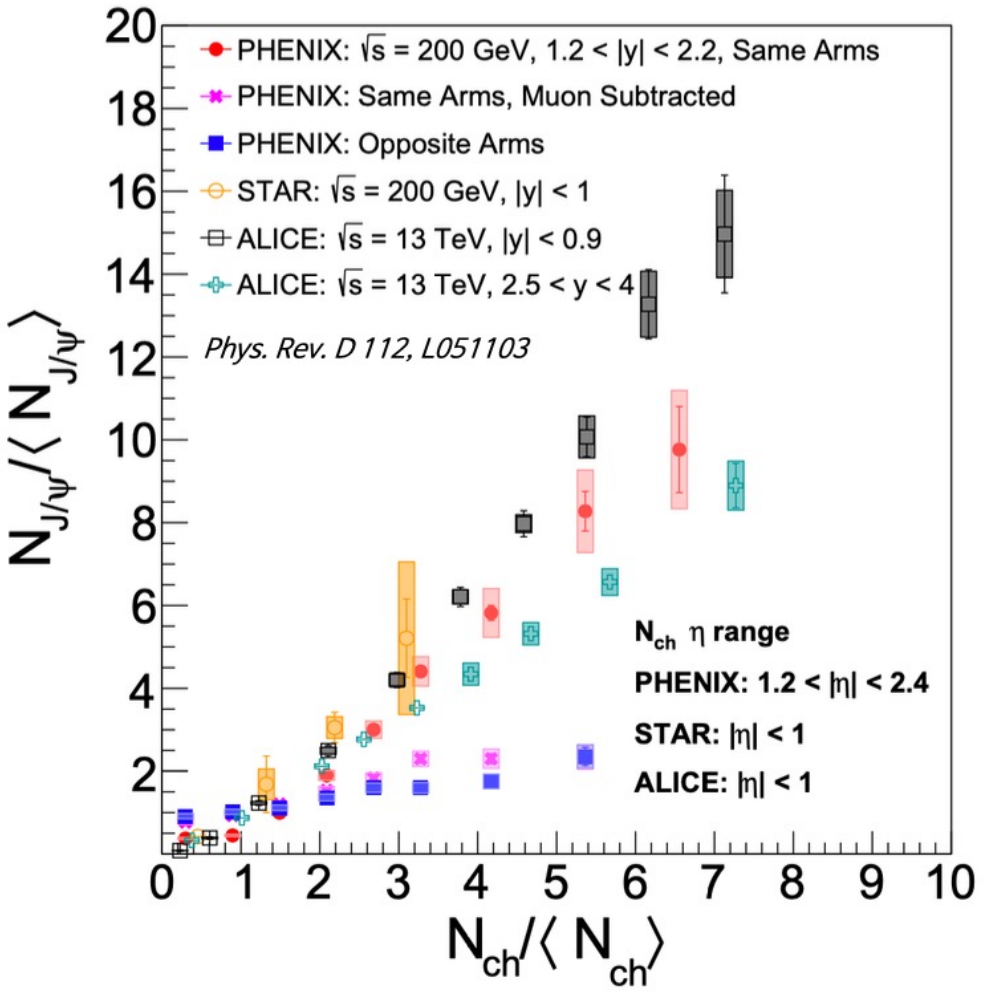




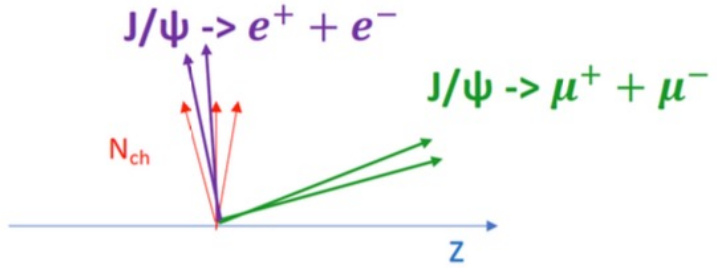
Phys. Rev. D 112, L051103

- J/ψ relative yields compared with PYTHIA8 Detroit tune for RHIC energies
- Multiparton interactions are required to reproduce PHENIX data

Comparison with results from other experiments



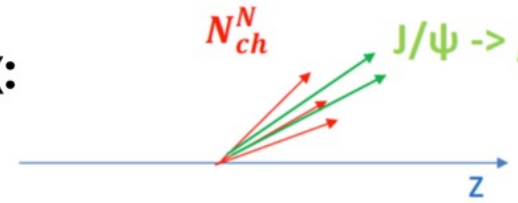
ALICE:



STAR:



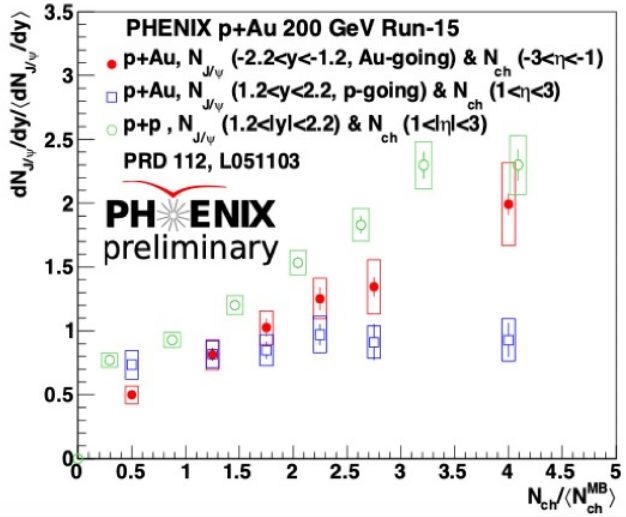
PHENIX:

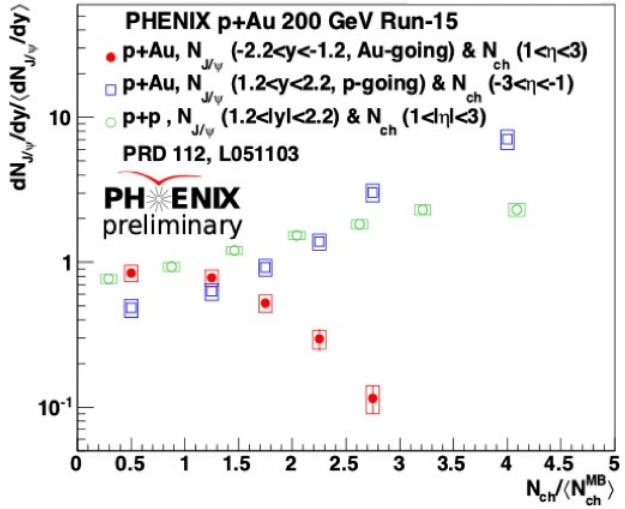


- **Without subtraction** of muons from J/ψ in N_{ch}:
  Similar multiplicity dependence between RHIC and LHC results

Summary

- PHENIX has studied multiplicity-dependent charmonia production in small collision systems
- J/ψ yields as a function of multiplicity in p+p:
  Increasing yields as multiplicity increases
  - PYTHIA8 Detroit tune with MPI can describe the data
  - Multiplicity dependence is smaller than LHC results
- J/ψ yields as a function of multiplicity in p+Au:
  - Very different trend depending on the combination of rapidity windows for J/ψ and multiplicity measurements
  - No model fully describing the data





Multiparticle production in electron-positron annihilation

Elena Kokoulina, JINR & GSTU (Belarus)
Yara Shouha, JINR & Alexandria University, Egypt







54th International Symposium on Multiparticle Dynamics (ISMD2026)
National Central University in Chungli, Taiwan



Legendary Wu Chien-Shiung (By Цзянсюн) at JINR, Dubna in the 60s (ICHEP) shakes Nikitin's hand, famous Russian experimenter.

e^+e^- - annihilation

Konishi et al. & Giovannini [NP, 1979] described the qg-cascade in pQCD as Markovian branching processes of elementary events:

1) quark bremsstrahlung - $q \to q + g$, ($\tilde{A}$)
2) gluon fission - $g \to g + g$, (A)
3) quark-antiquark pair creation from gluon - (B) $g \to q + \bar{q}$

$$\begin{cases} \dfrac{\partial G}{\partial Y} = -AG + AG^2, \\ \dfrac{\partial Q}{\partial Y} = -\tilde{A}Q + \tilde{A}QG. \end{cases}$$

System of diff. eq. describing branching processes, leads to Pólya (NBD) for q-jet and Yule-Furry MD for g-jet:

$$P_m^g = \frac{1}{\bar{m}}\left(1 - \frac{1}{\bar{m}}\right)^{m-1},$$

$$P_m^q = \frac{k_p(k_p+1)\ldots(k_p+m-1)}{m!}\left(\frac{\bar{m}}{\bar{m}+k_p}\right)^m\left(\frac{k_p}{\bar{m}+k_p}\right)^{k_p}.$$

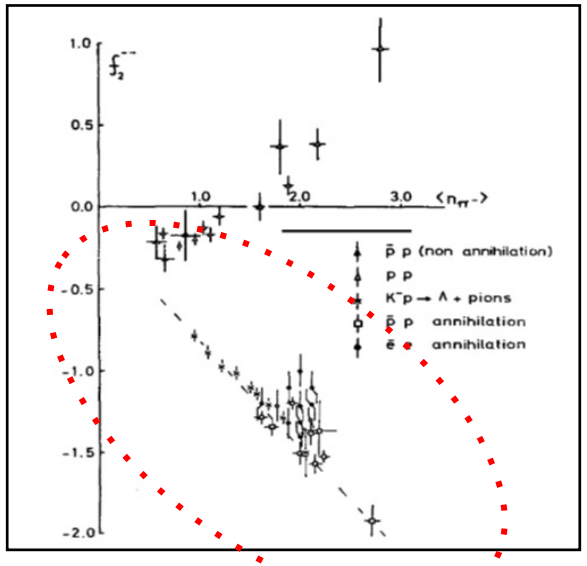
Evolutinary parameter:

$$Y = \frac{1}{2\pi b}\ln[1 + ab\ln(Q^2/\mu^2)],$$

$\tilde{A}$ и A ~ probabilities of 1) и 2) events, $k_p = \tilde{A}/A$.

e^+e^- annihilation - II stage

pQCD is unable to describe hadronization. The choice of MD at this stage is based on experimental behavior of the second correlative moment f_2. It is always positive for Pólya (NBD):



J.G. Rushbrooke, B.R. Webber. Phys. Rep. 44 (1978) 1

NBD → $$f_2 = \overline{n(n-1)} - \overline{n}^2 \to \frac{\overline{m}^2}{k_p} > 0$$

Choose binomial MD (Bernoulli) for the II-stage:

$$P_P^H(n) = C_{N_p}^n \left(\frac{\overline{n}_p^h}{N_p}\right)^n \left(1 - \frac{\overline{n}_p^h}{N_p}\right)^{N_p - n}, P = q, g.$$

$$f_2 = -\frac{(\overline{n}_p^h)^2}{N_p} < 0.$$

Convolution of two stages → Gluon Dominance Model (GDM)

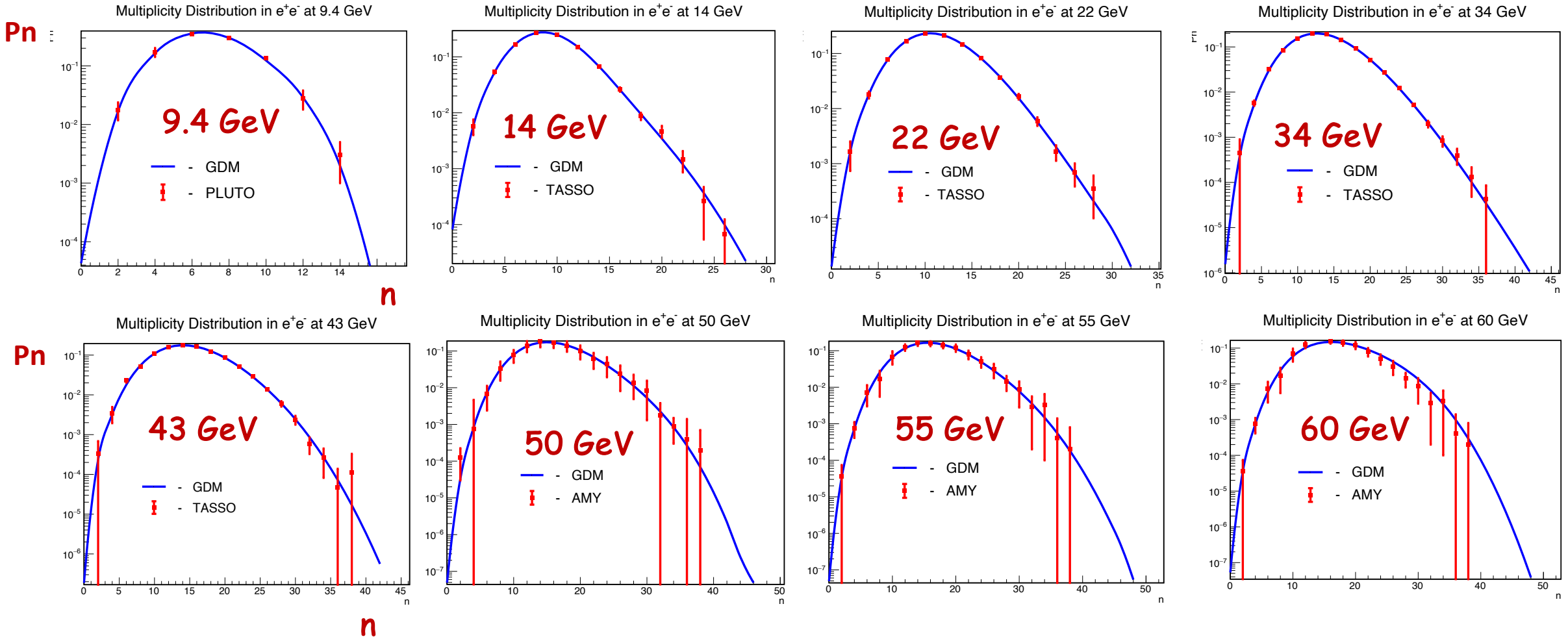
$$Q(s,z) = \sum_m P_m^P Q^H(m,s,z)$$ (soft discoloration).

$$P_n(s) = \Omega \sum_{m=0}^{M_g} P_m^P C_{(2+\alpha m)N}^n \left(\frac{\bar{n}^h}{N}\right)^n \left(1-\frac{\bar{n}^h}{N}\right)^{(2+\alpha m)N-n}$$

$$Q_p^H = \left[1+\frac{\bar{n}_p^h}{N_p}(z-1)\right]^{N_p}, \qquad p = q, g,$$

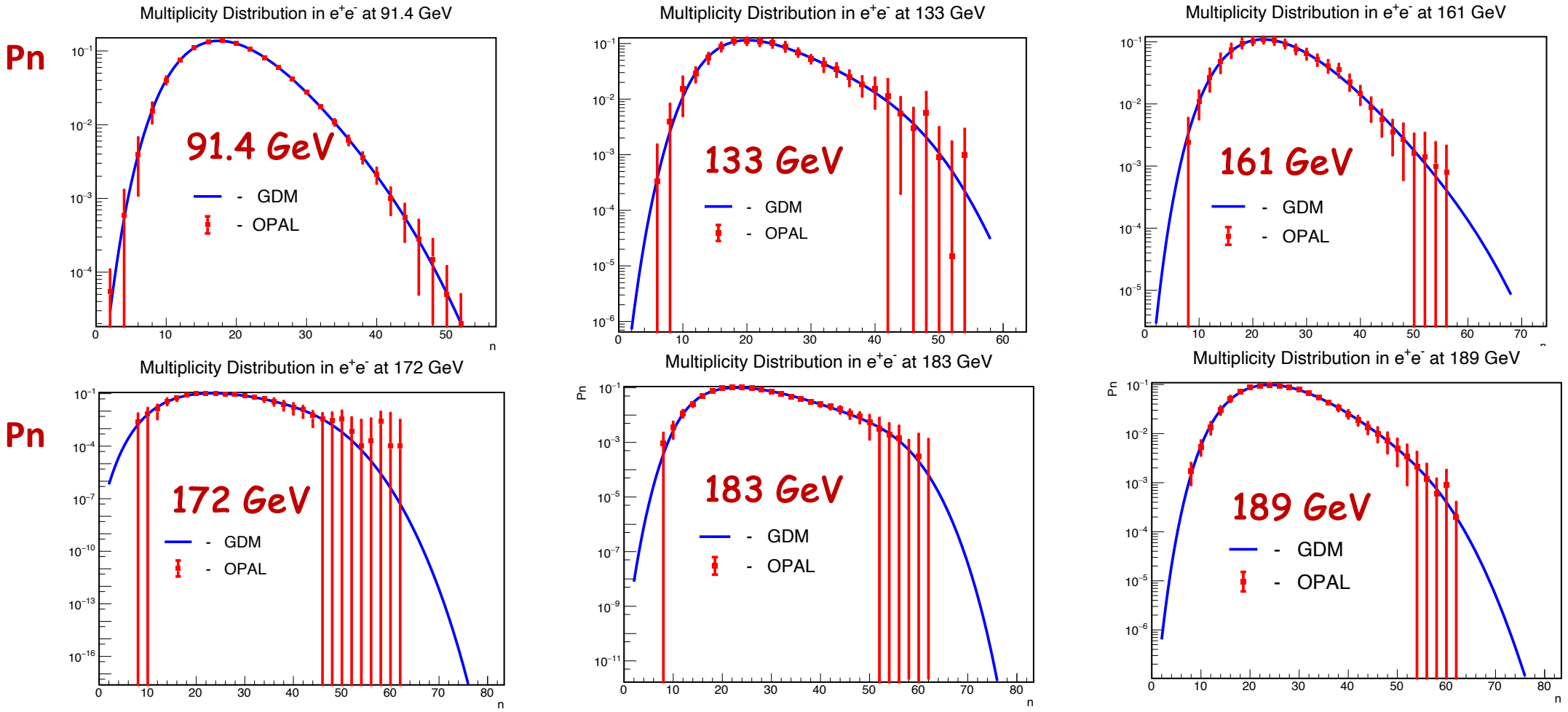
Model parameters: $k_p,\ \bar{m}\ ,\ \ N_q = N,\ \bar{n}_q^h,\ N_g = \alpha N, \bar{n}_g^h = \alpha \bar{n}_q^h$.

MD in e+e- annihilation (9.4 -61.4 GeV)



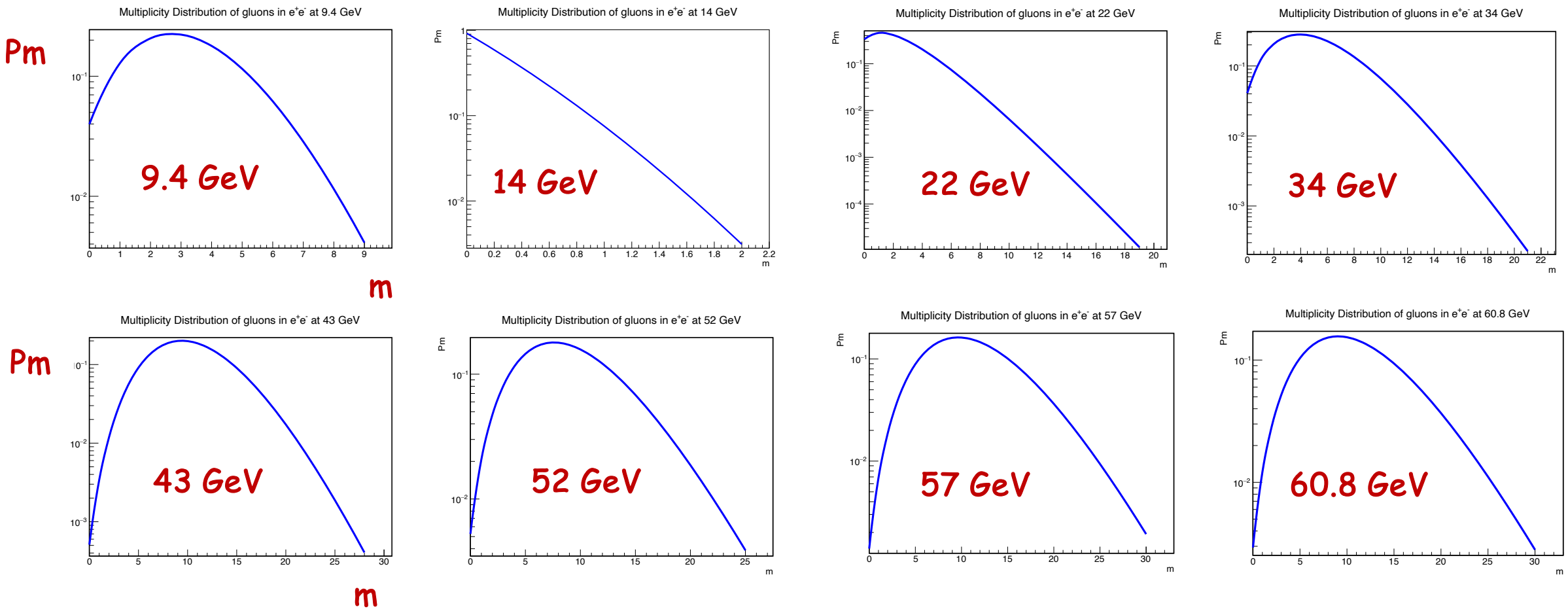
PLUTO [Phys. Lett. 95 (1980) 313]. TASSO [Z. Phys. C 22 (1984) 307]. AMY [Phys. Rev. D 42 (1990) 737]

MD in e+e- annihilation (91.4 -189 GeV)

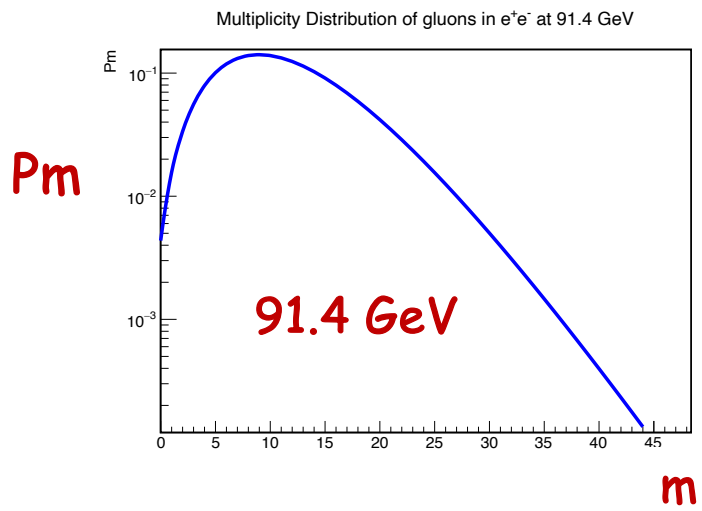


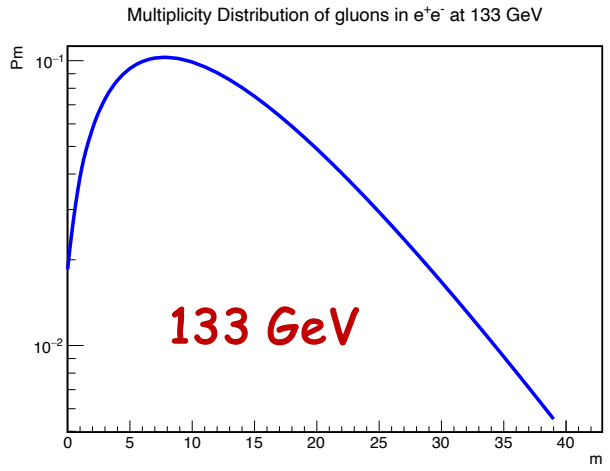
OPAL: J.Phys. C 52 (1991) 271; Z. Phys. C 72 (1996) 191; CERN-PPE/97-015; hep-ex/0002012.

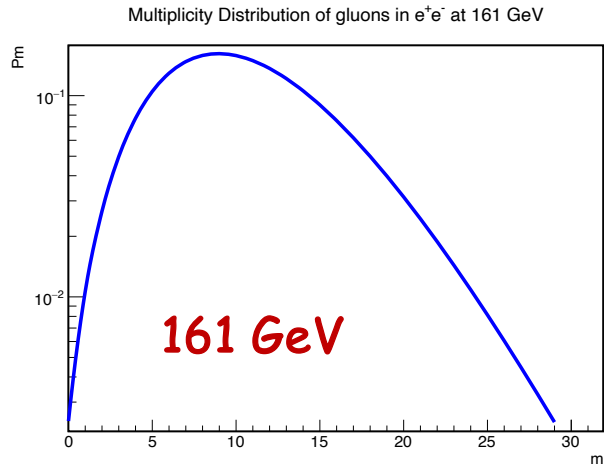
MD of gluons in e+e- annihilation (9.4 -61.4 GeV)

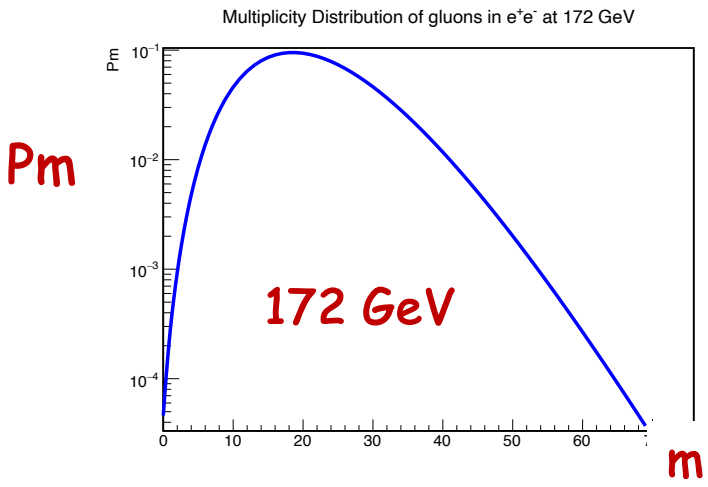


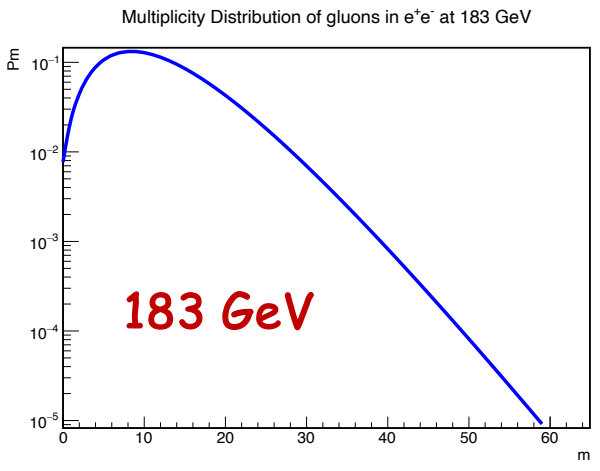
MD of gluons in e+e- annihilation (91.4 -189 GeV)

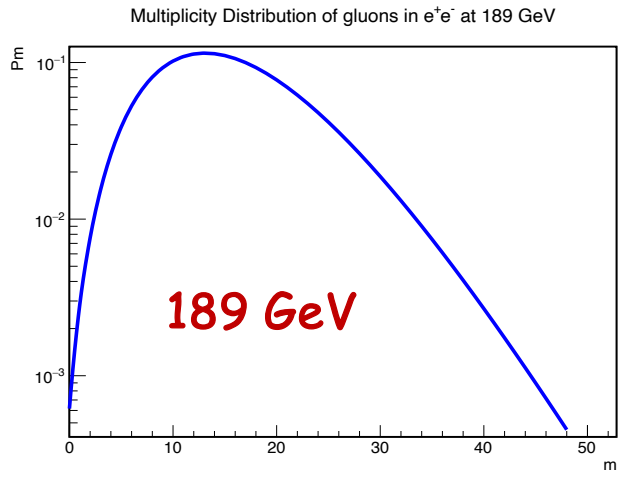






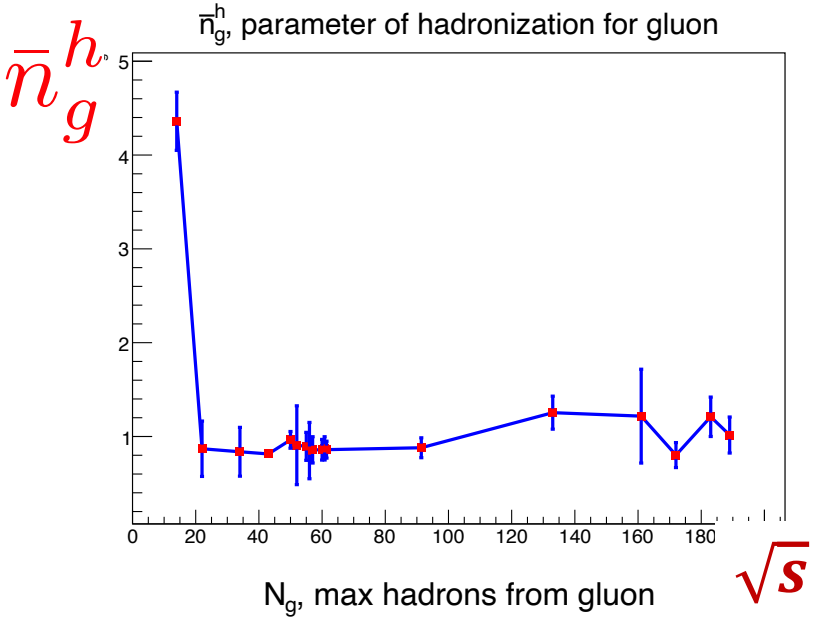


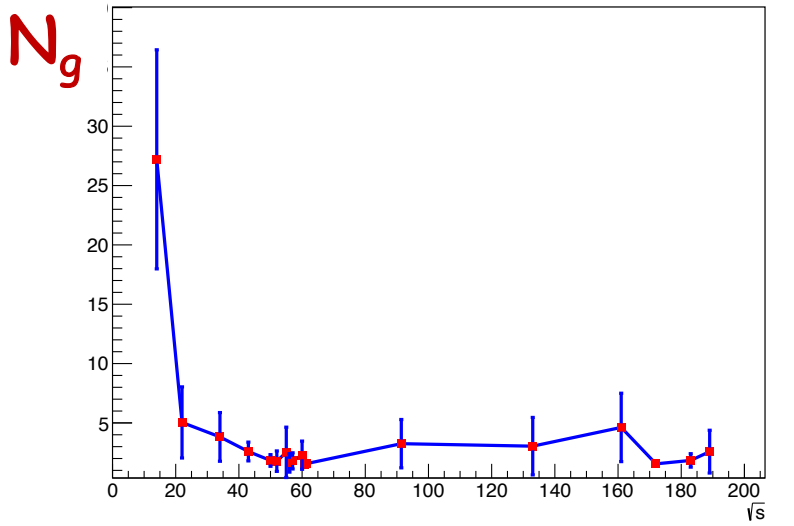




We find out that gluons are produced with ease before hadronization unlike hadrons.

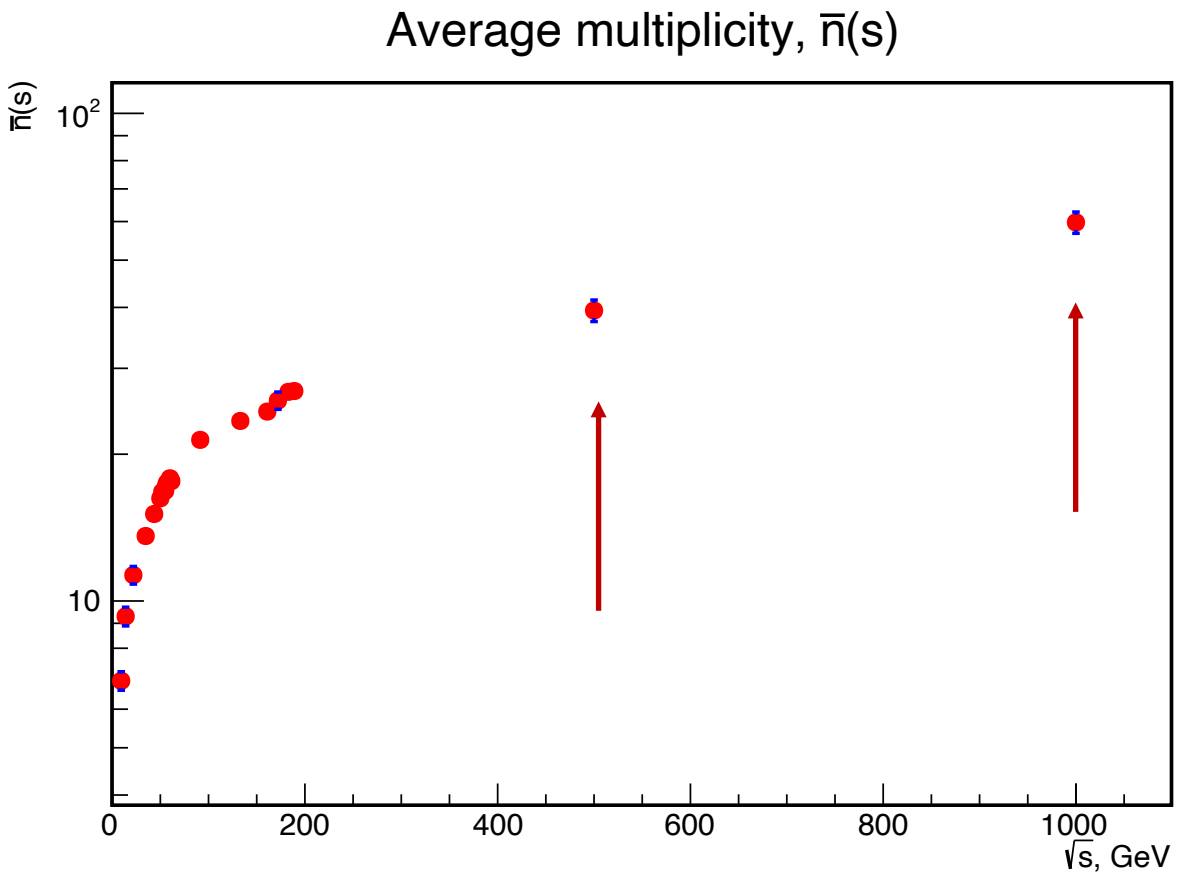
Parameters of gluon, $\bar{n}_g^h$, N_g





$\sqrt{s}$ = 9.4 GeV: $\bar{m}$ ~ 3
(only q-bremsstrahlung without g-fission).
$\sqrt{s}$ = 14 GeV: $\bar{m} = .08 \pm .05$
$\sqrt{s} \geq$ 22 GeV g–fission is turned on, $\bar{n}_g^h$ remains constant and less than 1 up to ~100 GeV (fragmentation mechanism), then it starts to grow and gently exceeds 1 (recombination mechanism) at ≳130 GeV.
Timid voices, based on LEP data, are heard about these signals.

Prediction for mean multiplicity at 500 GeV and 1 TeV:



Prediction: $\bar{n}(500\ \mathrm{GeV}) = 32 \div 39$ & $\bar{n}(1\ \mathrm{TeV}) = 37 \div 60$.

In 1994, while in Taiwan, Igor Dremin proposed exploring ratios:

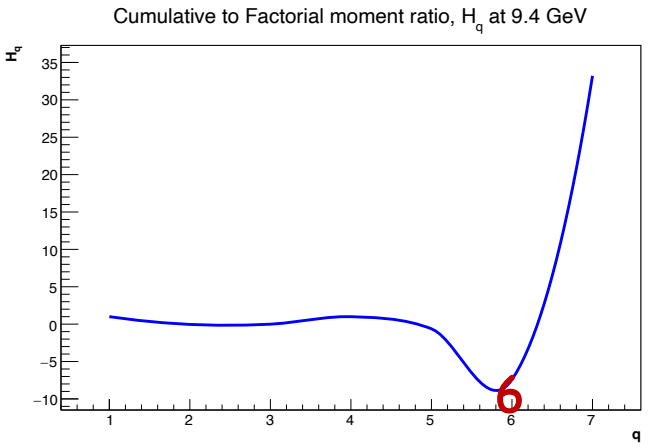
$$H_q = \frac{K_q}{F_q}, \qquad \text{where}$$

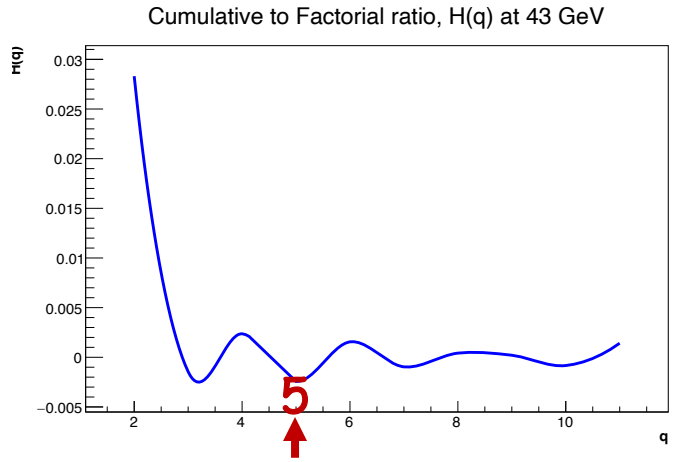
$$F_q = \overline{n(n-1)\cdots(n-q+1)}/\bar{n}^q, \qquad F_q \text{ - factorial moments}$$

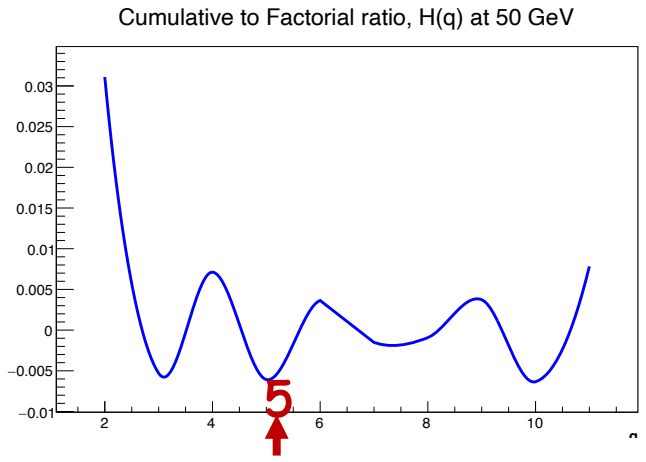
$$F_q = \sum_{m=0}^{q-1} C_{q-1}^{m} K_{q-m} F_m, \qquad K_q \text{ - cumulants, q – their rangs}$$

H_q for hadrons & gluons in GDM (preliminary)

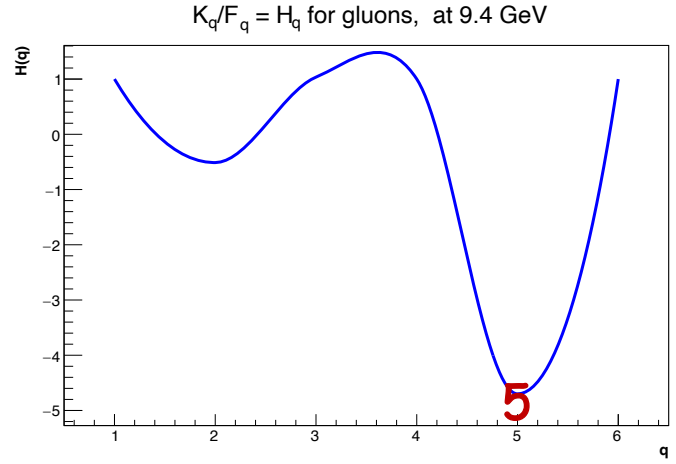
hadrons

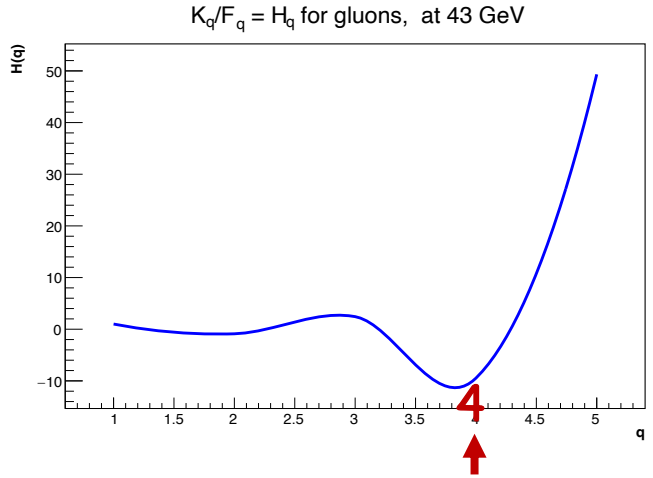


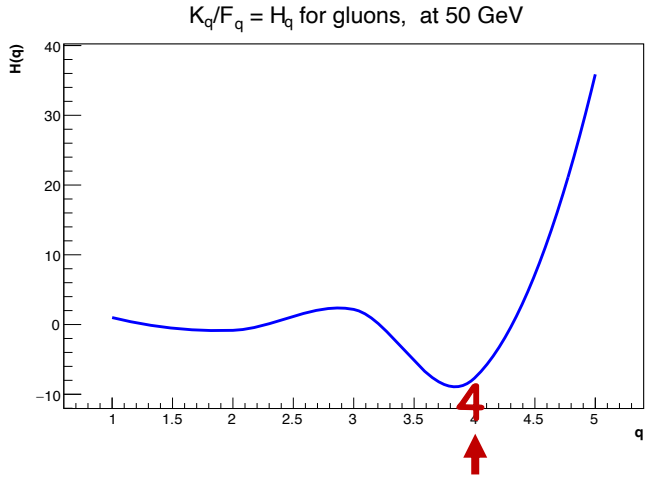




gluons

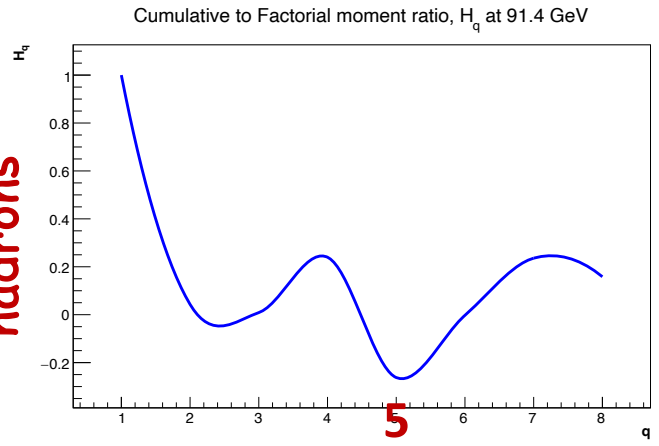


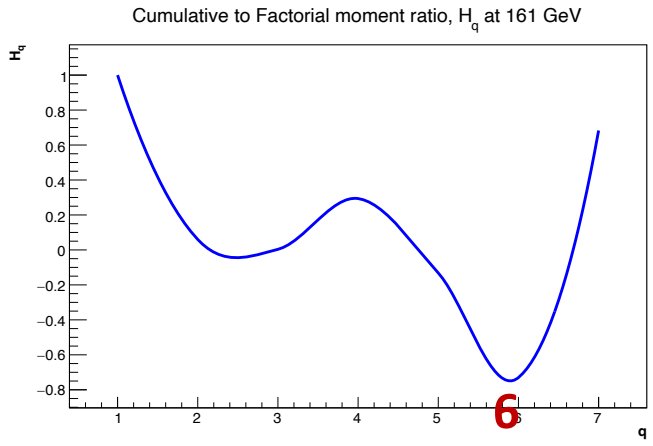


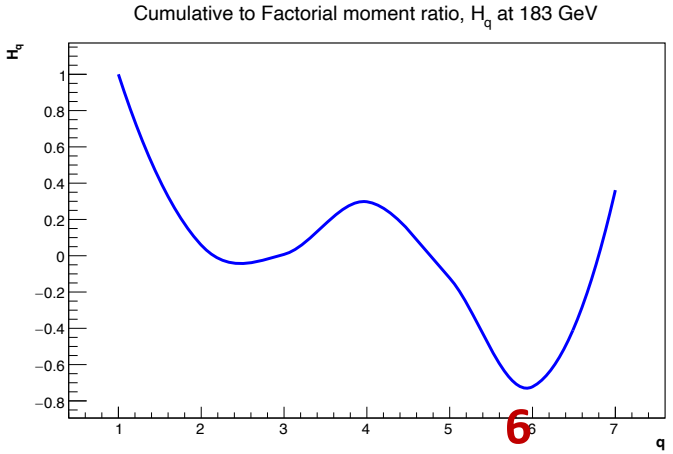


H_q for hadrons & gluons in GDM (preliminary)

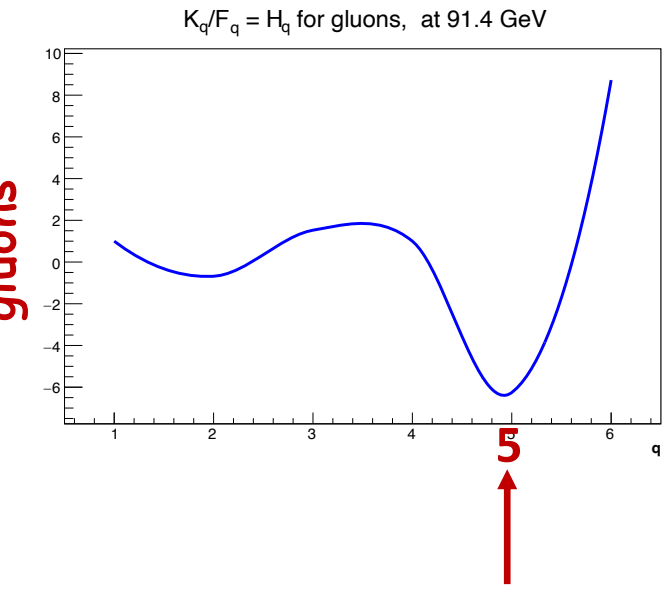
hadrons

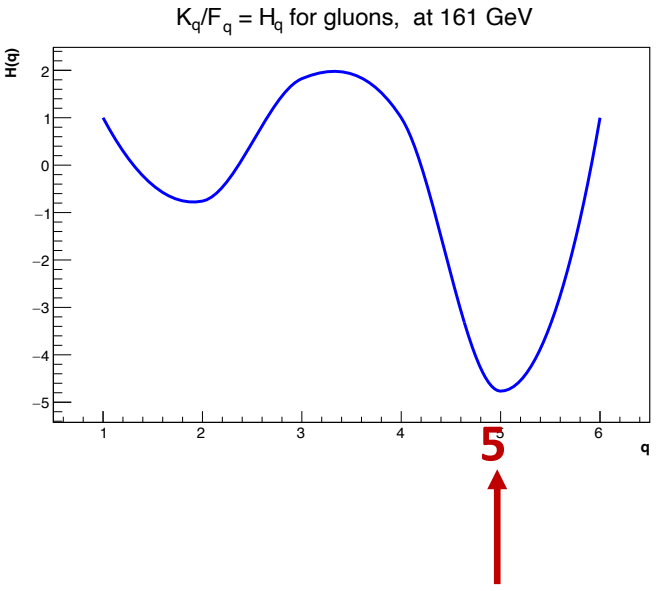


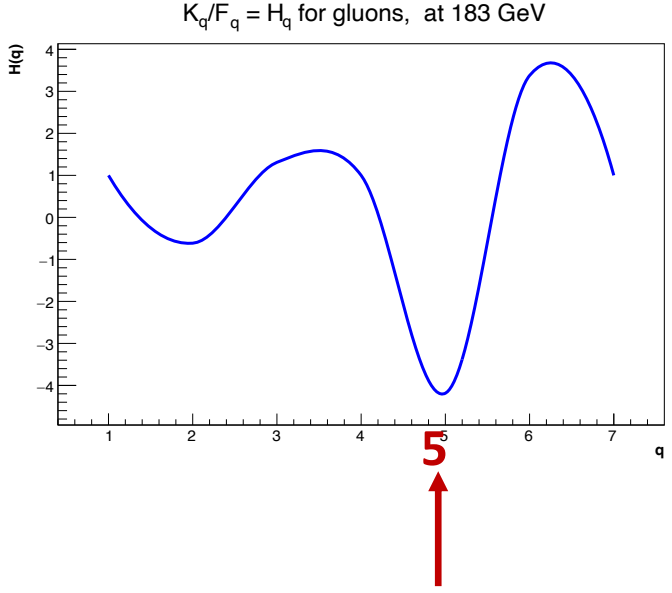




gluons







Investigating Collectivity and Strangeness Enhancement in e^+e^- collisions

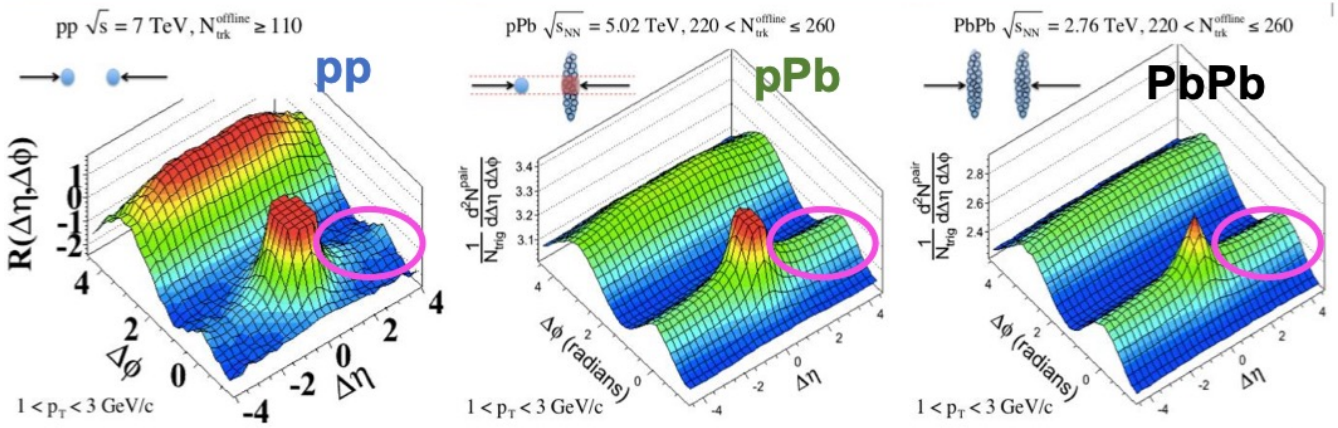
Yen-Jie Lee

for the e^+e^- alliance

54th International Symposium on Multiparticle Dynamics (ISMD 2026)
National Central University, Chungli, Taiwan
August 17, 2026

MIT HIG group's work was supported by US DOE-NP

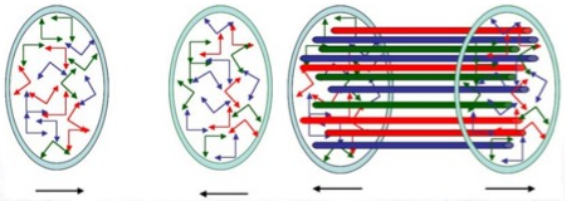
Interpretation of the Ridge Signal



Ridge signal was observed in high multiplicity pp and pPb

Possible Explanations:

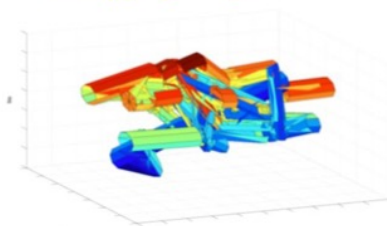
- Initial state effect (e.g. CGC)



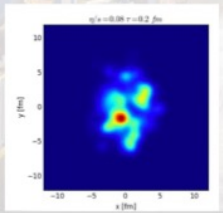
- Escape mechanism / Single or few scatterings (AMPT, PYTHIA with Rope Mechanism, Multi-parton rescattering…)



Overlapping strings in PYTHIA



- Final state effect due to mini-QGP production



- …

pp: CMS JHEP 09 (2010) 091
pPb: CMS pPb PLB 718 (2013) 795-814

Physics Questions to be Addressed

- What are the minimum conditions for ridge signal in a small system?

  Vary the transverse size and multiplicity of the collision system

- Can detectable collectivity arise from final state effects unrelated to the initial state?

  Use electron beams that do not carry hadronic PDFs or beam remnants

- How does collectivity vary in different physics processes?

  Select and study specific physics processes

- Is the underlying physics the same in small and large systems?

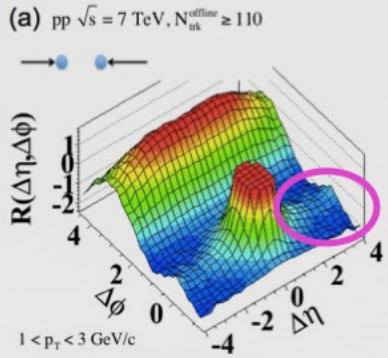
  Collect data across systems and compare systematically

- …

Smallest System: e^+e^-

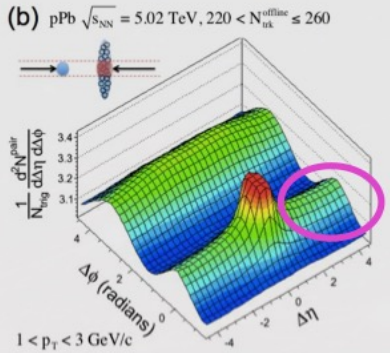
"Transverse Size" / MPI

High multiplicity pp

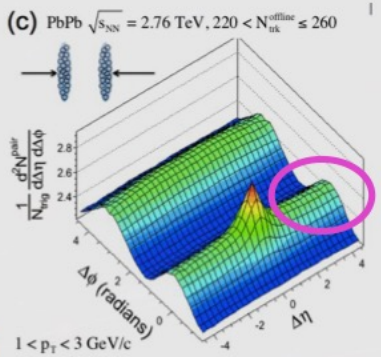


~ O(1fm)

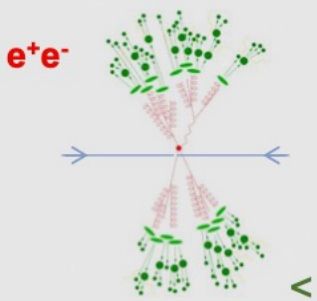
High multiplicity pPb



≥ O(1fm)



O(1-10 fm)



< 0.1 fm

- e^+e^- events: collisions with **well-defined initial conditions**
  - No complication from hadron structure
  - No multi-parton interaction
  - No gluonic initial state radiation

Multiplicity

Electron-Positron Alliance


Janice Chen (MIT)


Austin Baty (UIC)

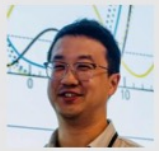

Chris McGinn (MIT)

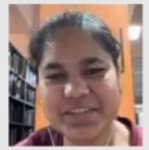

Michael Peters (MIT)


Anthony Badea (UChicago)


Paoti Chang (NTU)


Cen Mo (SJTU)

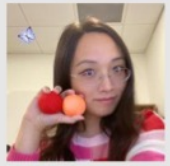

Yulei Zhang U. Washington


Honey Khindri (IIT Madras)




Tzu-An Sheng (MIT)


Ben Nachman (Stanford/SLAC)


Yi Chen (Vanderbilt)


Jingyu Zhang (Vanderbilt)


Luke Lu (Vanderbilt)


MJ Khan (Vanderbilt)


Chen-Hua Hsu (NTU)


Xiaoyuan Zhang (MIT)


Hannah Bossi (MIT)


Gian Innocenti (MIT)


Jesse Thaler (MIT)


Marcello Maggi (INFN Bari)


Günther Dissertori (ETH Zürich)

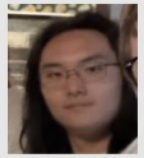

Nishant Gaurav (Vanderbilt)


David d'Enterria (CERN)

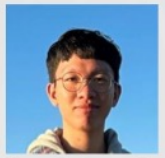

Yen-Jie Lee (MIT)


Jeetendra Gupta (UIC)

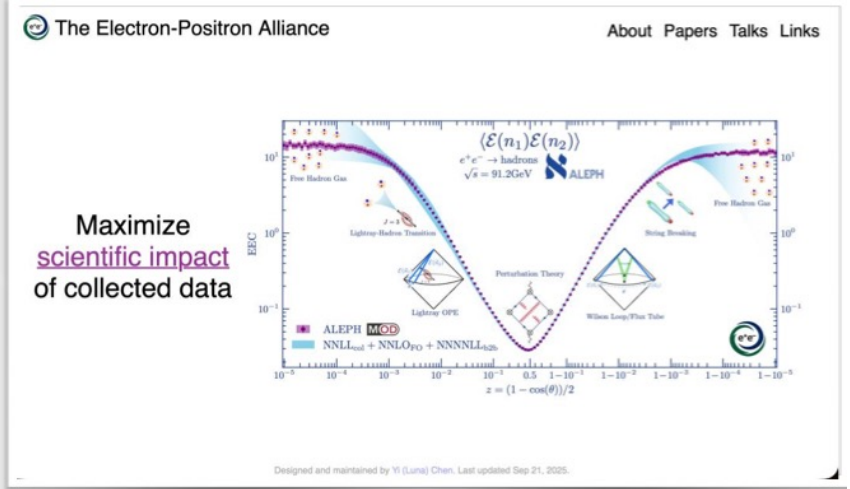
Sascha Diefenbacher (LBNL)


Bill Zhou (Vanderbilt)


Cristian Baldenegro (MIT)


Ting-Hsiang Hsu (NTU)


Prabhat Pujahari (IIT Madras)

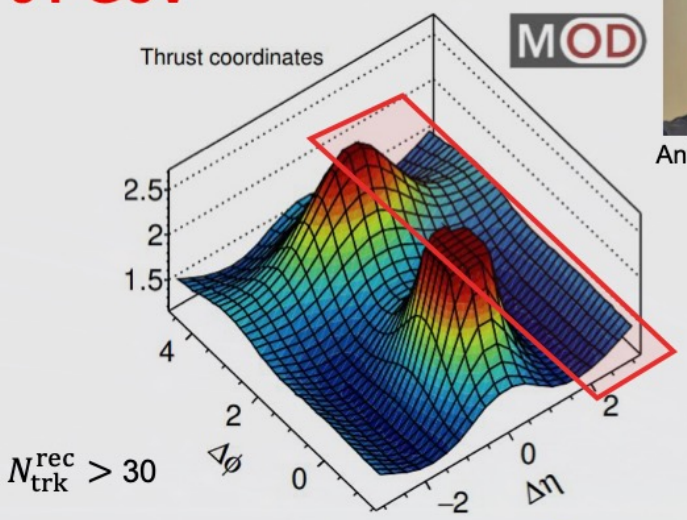


Topics includes: precision QCD, high density QCD, Quantum correlation, precision EWK, agentic AI for HEP exploration, development of techniques for FCC-ee …

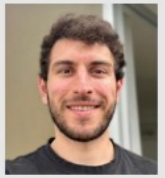
https://ee-alliance.org

e^+e^- at 10.52 (Belle) and 91 GeV (ALEPH)

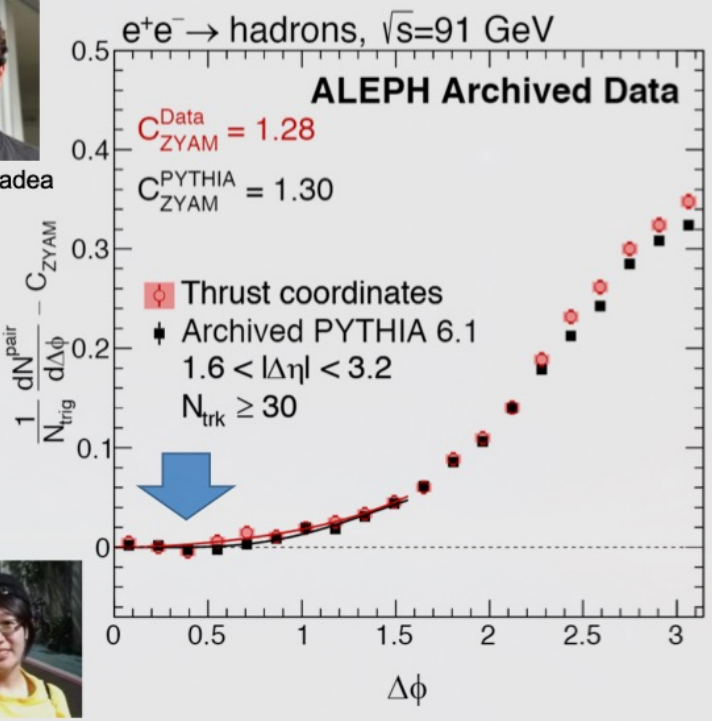
91 GeV

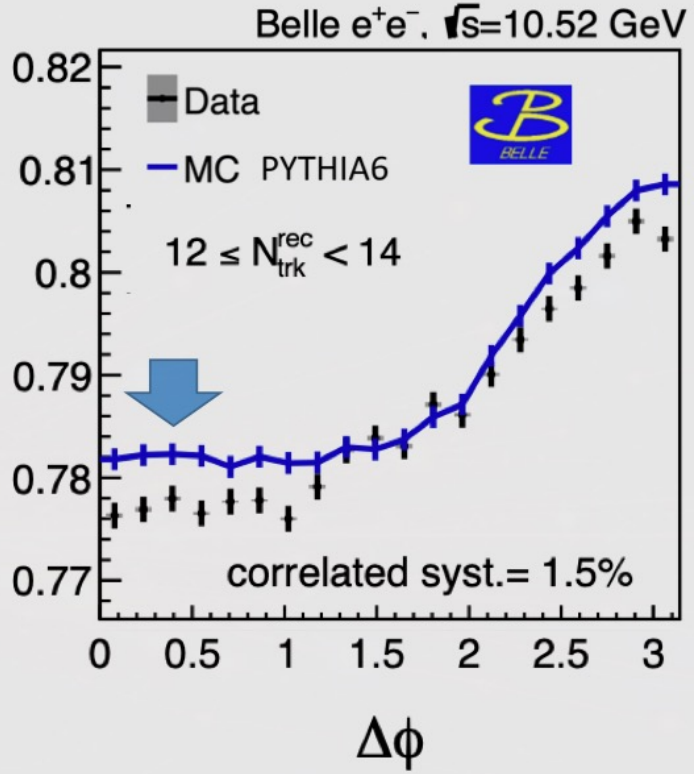


MOD



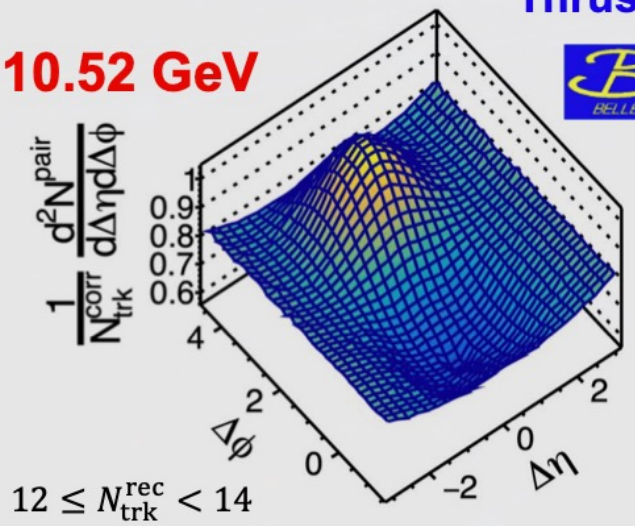
Anthony Badea

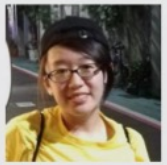




Thrust

10.52 GeV





Yu-Chen "Janice" Chen

- No sign of ridge signal in high multiplicity electron-positron collisions up to ~35 charged particles per event
- New reference to the collective behavior in small systems!

ALEPH archived data PRL 123, 212002 (2019)

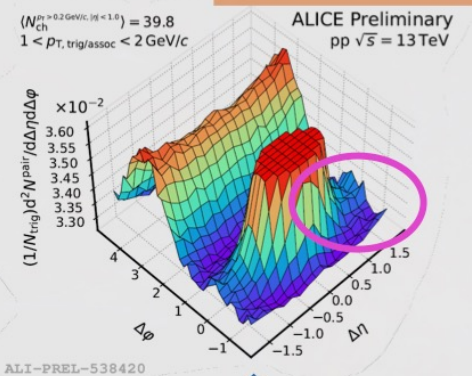
Off Y(4S) resonance, Belle PRL 128 (2022) 14, 142005

On Y(4S) resonance, Belle JHEP 03 (2023) 171

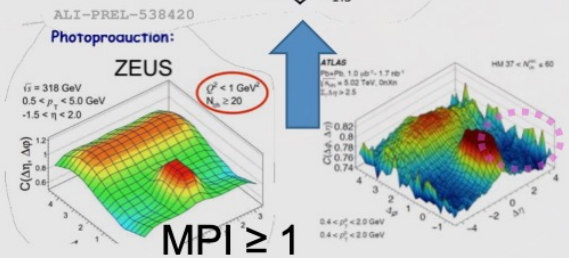
ALICE Low Multiplicity pp and CMS High Multiplicity Jet

"Transverse Size" / "MPI"

ALICE Low multiplicity pp signal

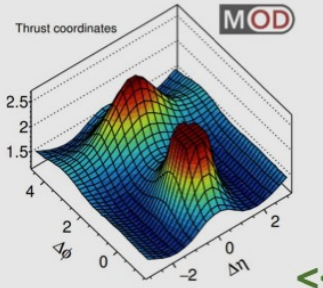


MPI>1



MPI ≥ 1

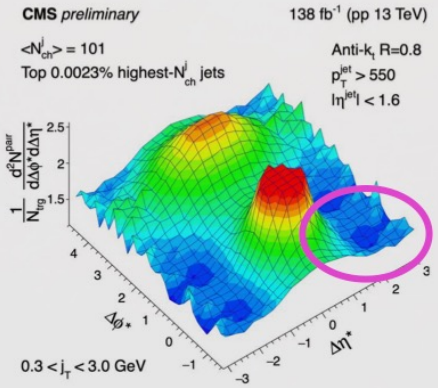
Larger MPI than γp

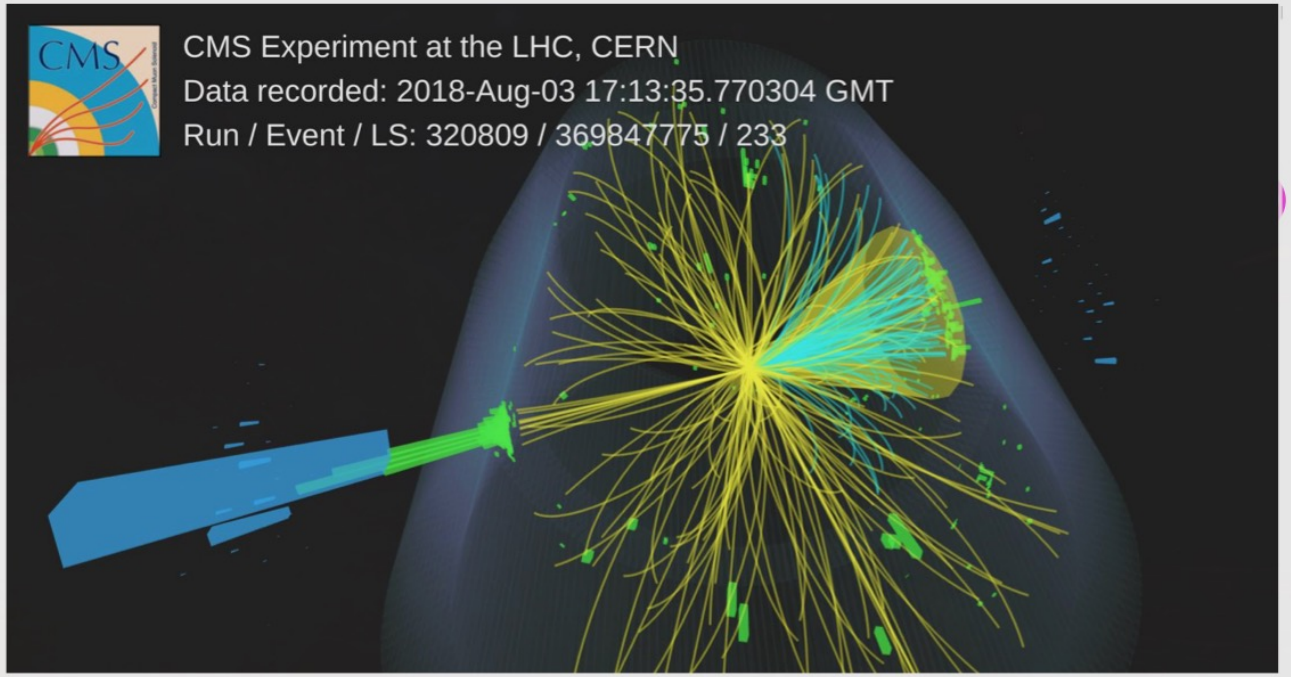


e^+e^-

"MPI"=1

<< 0.1 fm



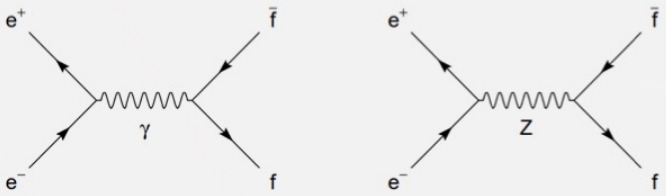


CMS High Multiplicity Jet

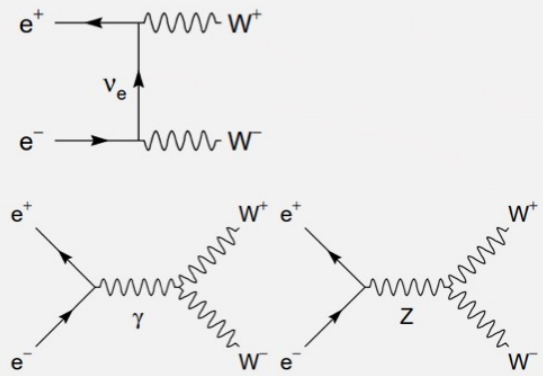
Multiplicity

Charged Particle Multiplicity Distributions in LEP2 Data

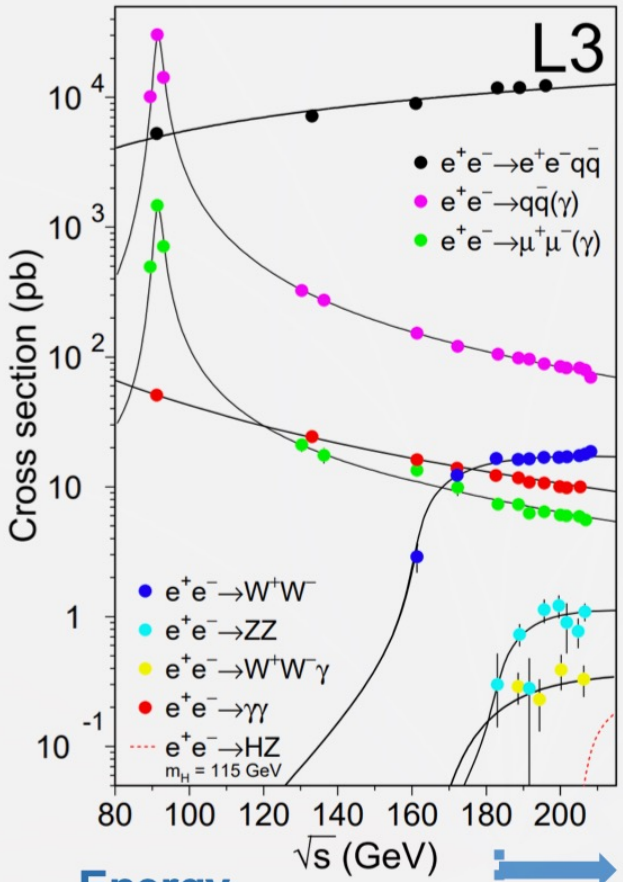
- $e^+e^- \to q\bar{q}(\gamma)$



- $e^+e^- \to W^+W^-$



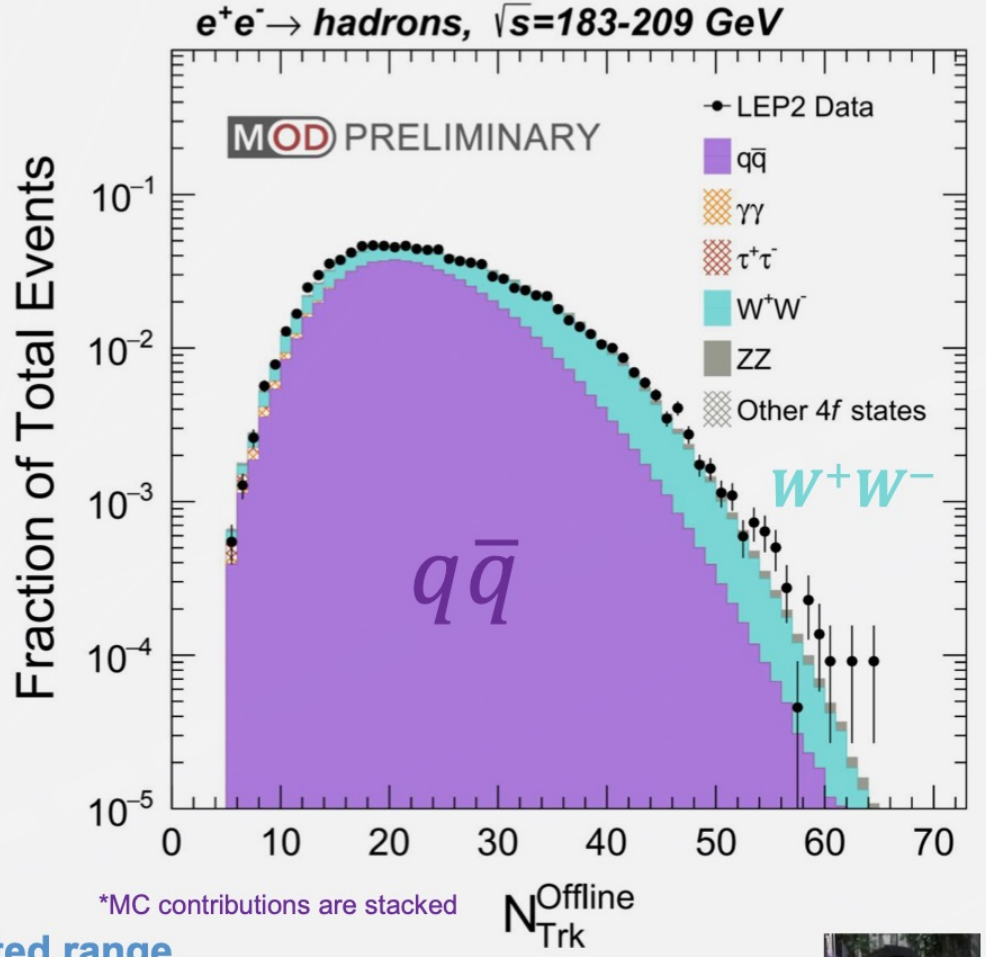
Phys. Rept. 532 (2013) 119-244



Energy

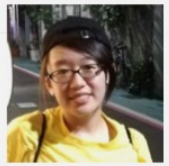
EPJC 63 611 (2009)

Reported range



*MC contributions are stacked

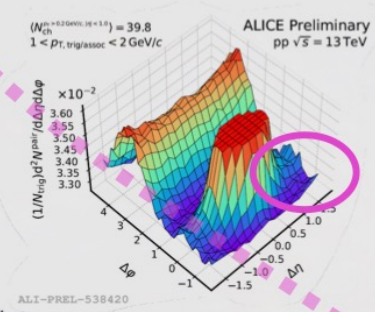
- **LEP2 energies** also give access to different physics processes
- At high multiplicity, W^+W^- contribution becomes significant



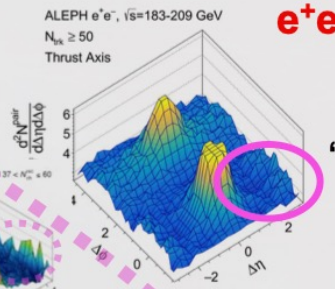
Yu-Chen "Janice" Chen (MIT)

Emerging Picture (Artist's impression)

"Transverse Size" / "MPI"

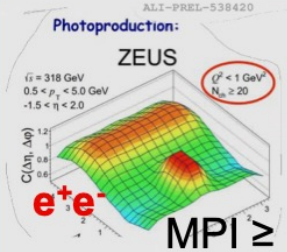


MPI>1

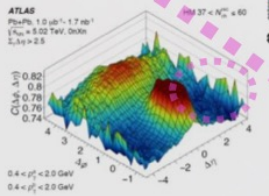


$e^+e^- \rightarrow W^+W^-$

"MPI"=2



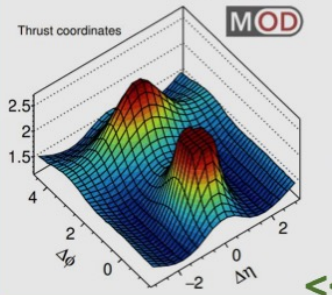
MPI ≥ 1



Larger MPI than γp

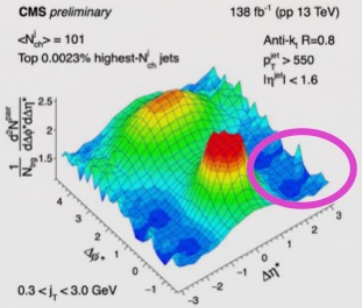
Ridge

No ridge

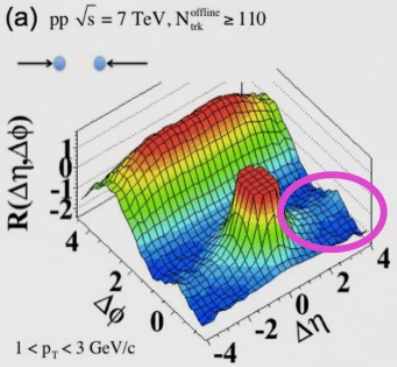


"MPI"=1

<< 0.1 fm

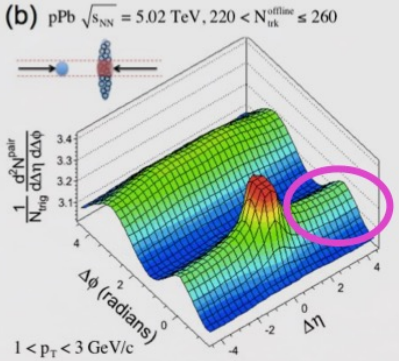


High multiplicity pp

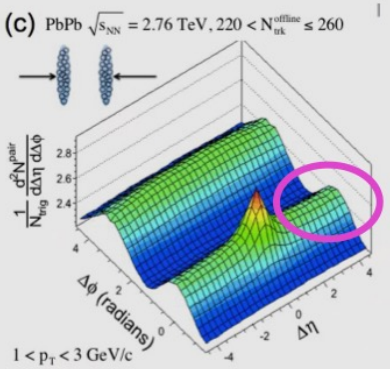


~ O(1fm)

High multiplicity pPb



≥ O(1fm)



O(1-10 fm)

Multiplicity

- Каковы min условия для сигнала ridge в малой системе? - Большие MPI и/или события с НМ помогают уменьшить $V_{1\Delta}$ и непосредственно выявляют гребень.
- Может ли обнаруживаемая коллективность возникать из эффектов конечного состояния, не связанных с начальным состоянием? - Признаки эффектов конечного состояния из данных CMS о одиночных струях с НМ и данных ALEPH LEP2.
- Как коллективность изменяется в различных физических процессах? - Однострунное e+e-→q$\bar{q}$ дает нулевую базовую линию. Двухструнное LEP2 e+e-->W+W- является наиболее чистым тестом геометрии конечного состояния.
- Одинакова ли лежащая в основе физика в малых и больших системах? - Данные показывают, что малые системы, в которых отсутствуют эффекты адронного начального состояния e+e-, все еще могут давать сигнал, подобный гребню. Нет значительного увеличения отношения K/π по сравнению с Mult.

Эти данные предполагают, что корреляции, подобные коллективности конечного состояния, могут возникать даже без структуры адронного начального состояния; механизм еще предстоит определить.