Nuclear matter studies at sPHENIX

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Drell-Yan process as a golden probe

How can we probe the gluon density in nuclei at sPHENIX?

References

- [Arleo, Naïm, Platchkov, JHEP01(2019)129]
- [Arleo, Naïm, JHEP07(2020)220]
- [sPH-TRG-2020-001]

Drell-Yan in proton-proton collisions

At large momentum transfer in pp, scale $Q \gg \Lambda_{QCD} \approx 200$ MeV

$$\mathrm{pp} \to \gamma^\star/Z^0 \to \ell^+\ell^- + \mathrm{X}$$

Factorization of cross section = approximation

$$\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y\mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1 f_i^{\mathrm{p}}(x_1, \mu) \int \mathrm{d}x_2 f_j^{\mathrm{p}}(x_2, \mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(x_1, x_2, \mu')}{\mathrm{d}y\mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{p}}^n}{Q^n}\right)$$

- x_1, x_2 : fraction of momentum carried by the parton in proton;
- $f_{i,j}$: Parton Distribution Function (PDF), *universal* non perturbative;
- $\hat{\sigma}_{ij}$: partonic cross section calculable in perturbation theory .

Drell-Yan partonic cross section very weel known!

Drell-Yan in proton-nucleus collisions

Cross section in pA collisions assuming collinear factorization

$$\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}y\mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1 f_i^{\mathrm{p}}(x_1,\mu) \int \mathrm{d}x_2 f_j^{\mathrm{A}}(x_2,\mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(x_1,x_2,\mu')}{\mathrm{d}y\mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{A}}^n}{Q^n}\right)$$

- Probing the PDF of a nucleus (without nuclear effects)

$$f_i^{\mathrm{A}} = Z f_i^{\mathrm{p}} + (A-Z) f_i^{\mathrm{n}}$$

$$\sigma_{\mathrm{pA}} = Z\sigma_{\mathrm{pp}} + (A-Z)\sigma_{\mathrm{pn}} \approx \mathrm{A}\sigma_{\mathrm{pp}}$$

Investigate nuclear effects via:

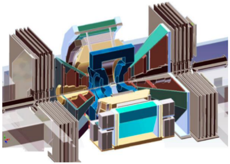
$$R_{\mathrm{pA}} \equiv \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}\sigma_{\mathrm{pp}}} \not\approx 1$$

because

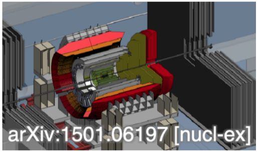
1. nuclear PDF effects (nPDF)
2. energy loss/broadening effects

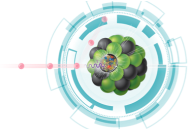
A transitional experiment...

- pp, pA, and AA data;
- QGP, Hadron Physics, CNM;
- 170+ physics papers with 24k citations;
- Last run in this form 2016.

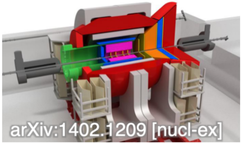


- pp, pA, and AA data;
- Jet and beauty quarkonia physics;
- Drell-Yan.



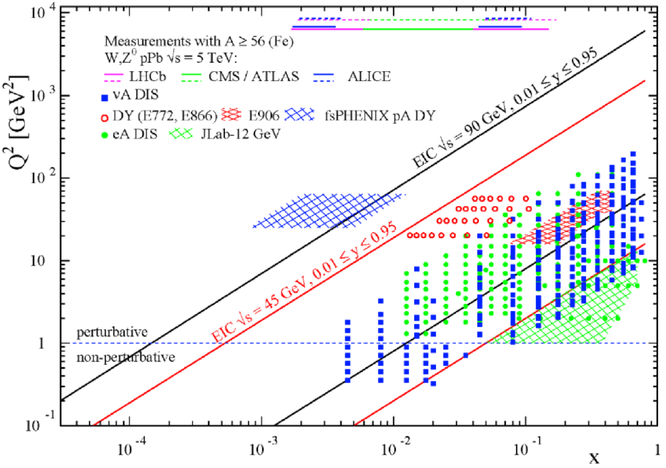


- ep and eA, with several nuclei;
- Transition PHENIX to EIC;
- Large coverage of tracking, calorimetry and PID.



2000 — **2017 - 2022** — **After 2025** — ***Time***

Drell-Yan at sPHENIX



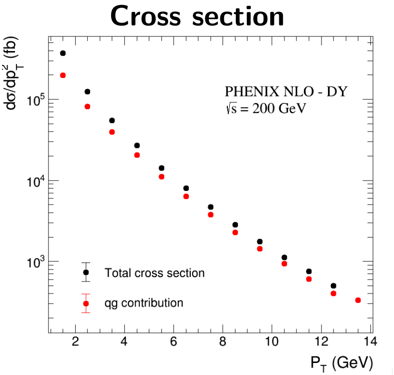
- Possible to access small $x \sim 10^{-2}$ to 10^{-3};
- **Complementary measurements from fixed targets to LHC**.

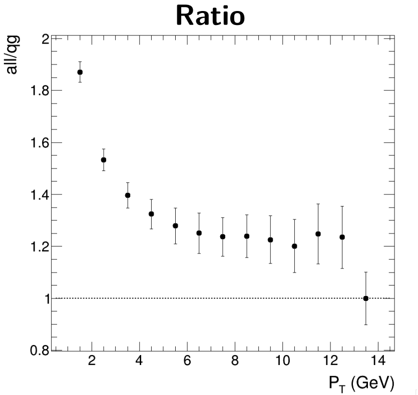
Luminosity expected at sPHENIX

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z \rvert$ <10 cm	Samp. Lum. $\lvert z \rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^\uparrow p^\uparrow$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^\uparrow$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

- **2024 (pp & pAu)**:
  Commissioning and pp reference data and pAu cold QCD;
- **2025 (AuAu)**:
  Large statistics data collection for jets and heavy flavor observables.

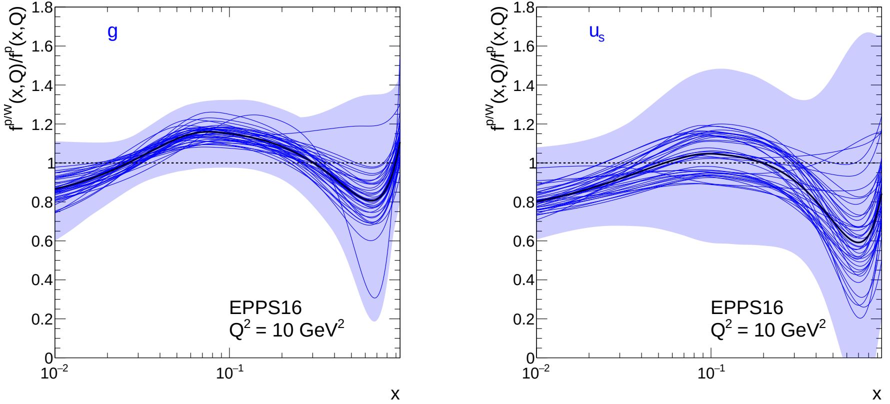
Drell-Yan at NLO - $\sqrt{s} = 200$ GeV - pp collisions





- At NLO: $q\bar{q} \to \gamma^*$ and qg$\to \gamma^*$q + X;
- qg contribution becomes significant at $p_\perp \sim 4$ GeV;
- $\sim$ 80 % of qg contribution for $4 \lesssim p_\perp \lesssim 15$ GeV.

nPDF (EPPS16)



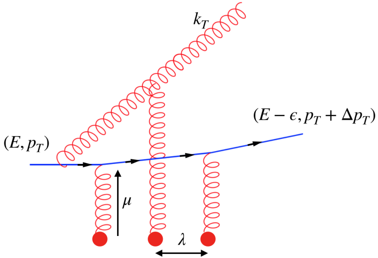
- $\sigma^{\mathrm{DY}} \propto \left(u^{\mathrm{p}}\bar{u}^{\mathrm{A}} + u^{\mathrm{A}}\bar{u}^{\mathrm{p}}\right)$ for $\mathrm{p}_\perp < \mathrm{M}$;
- $\sigma^{\mathrm{DY}} \propto \left(q^{\mathrm{p}}g^{\mathrm{A}} + q^{\mathrm{A}}g^{\mathrm{p}}\right)$ for $4 \lesssim \mathrm{p}_\perp \lesssim 15$ GeV;
- **Huge uncertainties**, especially in EMC/shadowing regions;
- Reduce others nPDF uncertainties thanks to DGLAP evolution.

Transport properties of cold nuclear matter (CNM)

Definition

$$\hat{q} \equiv \frac{\mu^2}{\lambda} = \frac{d\Delta p_\perp^2}{dL}$$

- λ is the parton mean free path in the medium;
- μ the typical momentum transferred during 1 soft collision;
- $\Delta p_\perp^2$ **the transverse momentum exchanged between the propating parton and the medium**.



CNM effects in Drell-Yan

Initial-state energy loss (small formation time $t_f \lesssim L$)

$$\langle E \rangle_{\text{LPM}} \propto \alpha_s \hat{q}\, L^2$$

Broadening effect

$$\Delta p_\perp^2 = \hat{q} L$$

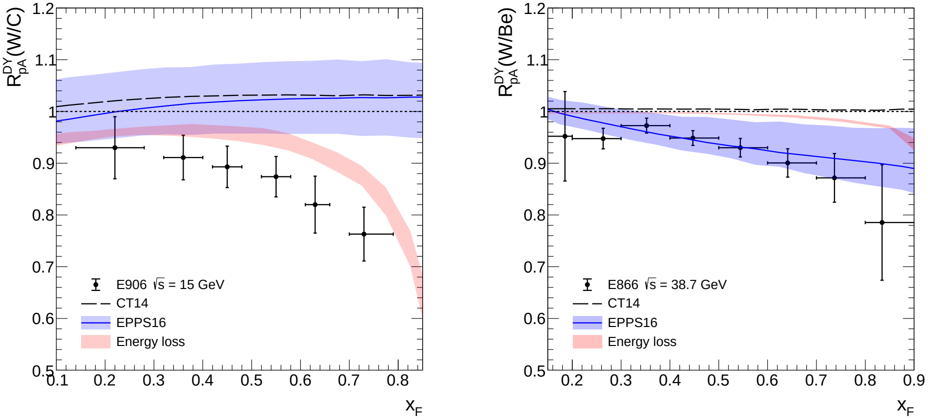
Transport coefficient: scattering property of the medium

$$\hat{q}\left(x, Q^2 = \Delta p_\perp^2\right) = \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1} \rho x G(x) = \hat{q}_0 \left[\frac{10^{-2}}{x}\right]^{0.3}$$

Two different obervables to probe the transport coefficient of CNM

Drell-Yan at SPS energy

[Arleo, Naïm, Platchkov, JHEP01(2019)129]

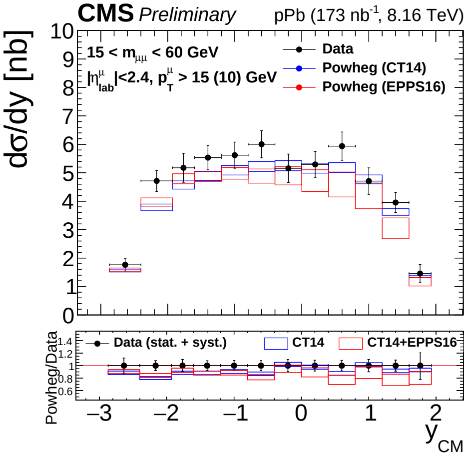


- **nPDF effect cannot alone describe prelimnary E906 data**;
- **Energy loss effect** at $\sqrt{s} = 15$ GeV leads to a **strong suppression**.

Drell-Yan at LHC energy

[CMS-PAS-HIN-18-003]

Drell-Yan in pPb at $\sqrt{s} = 8.16$ TeV



- **No suppression observed**;
- **LPM energy is suppresed at high beam energy**;
- DY at LHC/RHIC: **clean probe to constrain nPDF?**

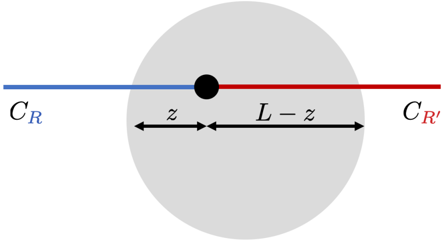
$\Delta E^{\mathrm{LPM}}/E \to 0$

Drell-Yan: a clean probe of the saturation scale I

$p_\perp$ spectra: an observable to probe transport properties

$$\Delta p_\perp^2 = \left\langle p_\perp^2 \right\rangle_{\rm hA} - \left\langle p_\perp^2 \right\rangle_{\rm hp} = \frac{C_R + C_{R'}}{2N_c} \left(\hat{q}_{\rm A} L_{\rm A} - \hat{q}_{\rm p} L_{\rm p}\right)$$

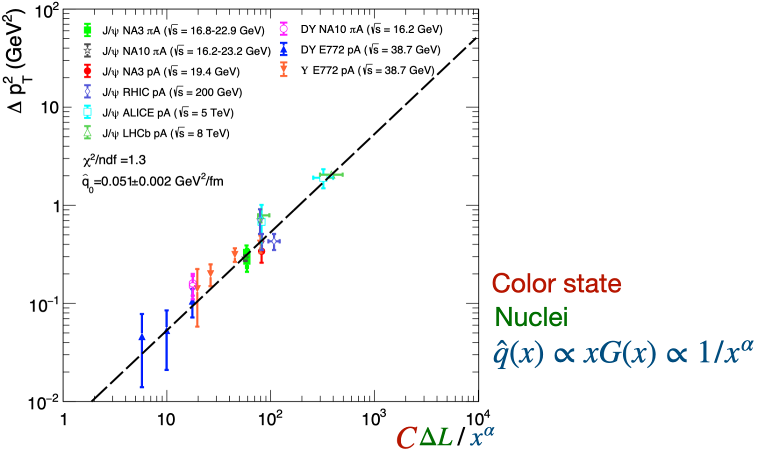
Low energy picture: $t_{\rm hard} \lesssim L$:



- Drell-Yan: $\mathcal{C}_q + 0 = 4/3$;
- Quarkonia (octet) in pA: $\mathcal{C}_g + \mathcal{C}_{[Q\bar{Q}]_8} = 3 + 3$.

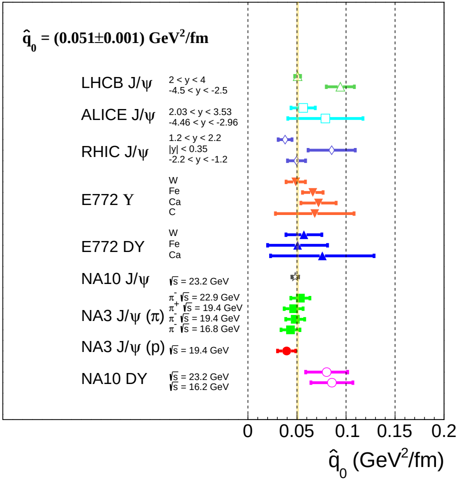
Drell-Yan: a clean probe of the saturation scale II

[Arleo, Naïm, JHEP07(2020)220]



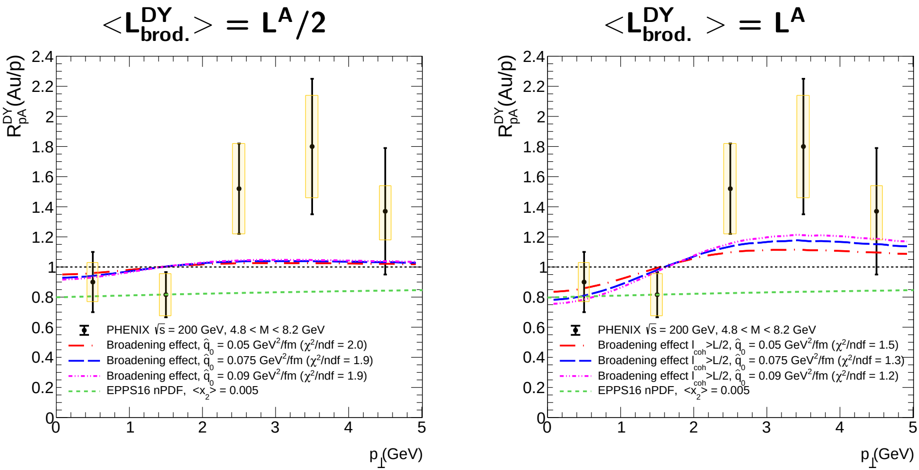
- Simple model used at high energy $\hat{q}(x) \propto \hat{q}_0 \times x^{-0.25}$;
- Extraction of $\hat{q}_0 = 0.051 \pm 0.02$ GeV^2/fm.

Extraction of the transport coefficient



- **New (strong?) constraint** from Drell-Yan data at sPHENIX.

Probe the coherence length via the broadening



- **Probe the coherence lenght** between low and high energy picture;
- Need to have better statistics to conclude $\rightarrow$ **sPHENIX experiment**.

Drell-Yan analysis at sPHENIX

Processes:

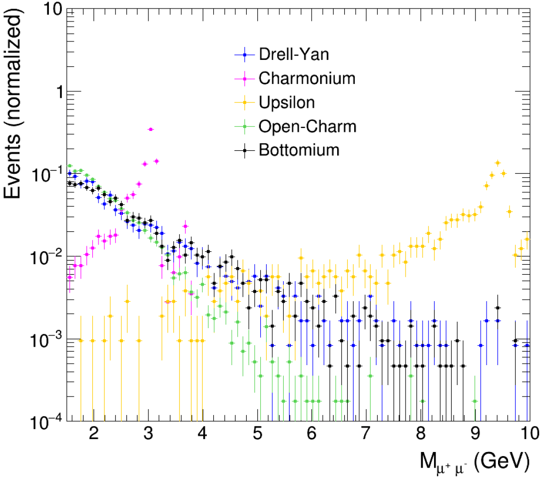
- Charmonium (J/ψ, ψ')
- Bottomonium (Υ)
- Open-Charm (D mesons)
- Bottom (B mesons)
- **Drell-Yan**

Procedure:

- **Simulate all QCD processes** in sPHENIX softwares and identify the contributiono of each of them in HMDY region (4 ¡ M ¡ 8 GeV);
- **Fit the mass spectrum** with the following function:

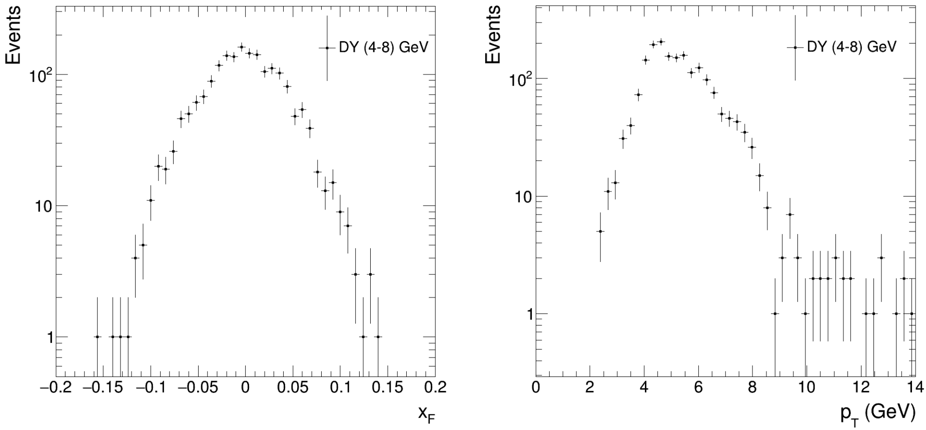
$$\mathrm{f(M)}_{\mathrm{fit}} = \alpha_1 f(M)^{\mathsf{Charmonium}}_{\mathrm{MC}} + \alpha_2 f(M)^{\mathsf{DY}}_{\mathrm{MC}} + \alpha_3 f(M)^{\mathrm{OC}}_{\mathrm{MC}} + \alpha_4 f(M)^{\mathrm{Bottom}}_{\mathrm{MC}} + \alpha_5 f(M)^{\mathsf{Bottomium}}_{\mathrm{MC}}$$

Simulation by using sPHENIX software



- **Very close shape** from DY, Bottomium and OC contributions;
- Bottom is **less steeper** compared to OC, especially at M $\gtrsim$ 4 GeV;
- **Tail from charmonium/bottomium at low mass**: QED radiation.

Drell-Yan - kinematic phase space



- Probe mainly high p_T: **good for gluons**!
- When $M \sim p_T$, $x_{1/2} \sim \sqrt{M^2 + p_T^2} e^{\pm y} / \sqrt{s}$;
- At forward: $x \sim 10^{-3} - 10^{-2}$, **shadowing region**.

Internal jet structure

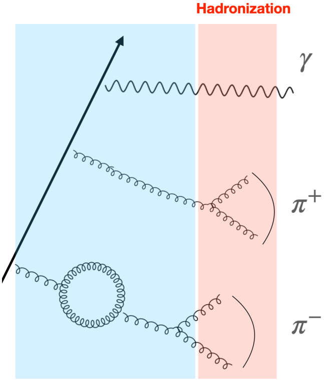
How can we probe the hadronization process at sPHENIX?

Reference

- [Y-T. Chien *et al.*, Phys Rev D.105.L051502]

Internal jet structure

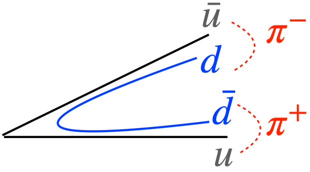
- Access the **dynamics of hadronization**;
- Charge-energy **correlation for Leading (L) and Next-to-Leading particles (NL)**.



Parton shower evolution + non-perturbative gluon splitting

Charge-energy correlation

- Compare the number of same charge particles h_1 and h_2 and the opposite charge particles h_1 and $\bar{h}_2$;
- **Access to the "string-like hadronization"**.

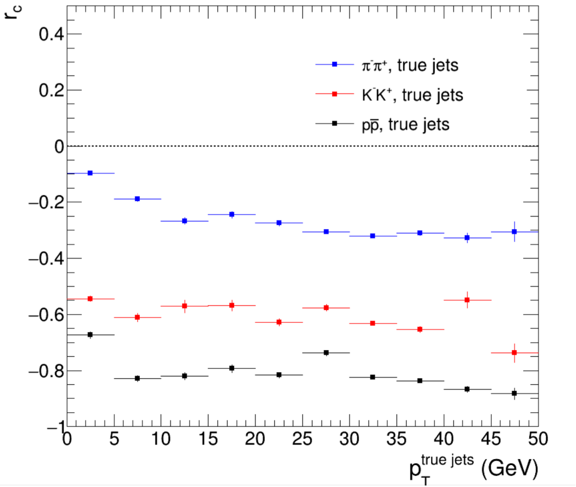


Observable:

$$r_c(X) = \frac{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X - \mathrm{d}\sigma_{h_1 \overline{h_2}}/\mathrm{d}X}{\mathrm{d}\sigma_{h_1 h_2}/\mathrm{d}X + \mathrm{d}\sigma_{h_1 \overline{h_2}}/\mathrm{d}X}$$

where h1 (L) ,h2 (NL) $\in (\pi^\pm, K^\pm, p)$

Charge-energy scaling



- **Significant differences** in r_c observed for various flavor combinations;
- **Remarkable scaling** as a functon of $p_\perp^{\text{jet}}$.

Hadronization process

Formation time

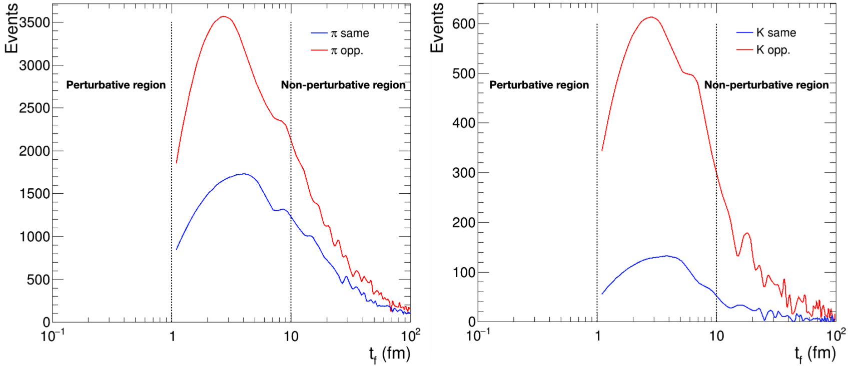
$$t_f = \frac{2z(1-z)P}{k_\perp^2}$$

- P: total momentum of L and NL particles;
- $k_\perp$: relative transverse momentum between L and NL particles;
- z: momentum fraction of NL particle.

Goals

- **Charge-energy correlation with** t_f for pions, kaons and protons;
- Probe **the flavor dependence of the hadronization process** inside a jet.

Formation time



- **Two relevant regions**:
  1. Perturbative region for $t_f \lesssim 10$ fm;
  2. Non-perturbative region for $t_f \gtrsim 10$ fm.
- **Difference in time formation** between different mesons.

Conclusion

Drell-Yan at sPHENIX

- **Unique opportunity to probe CNM effects**;
- **No LPM energy loss expected** at sPHENIX energy;
- **Complementary phase space** between fixed targets and LHC energies;
- Can give an **additional contraint** on the transport coefficient.

Not only DY ... *use the mass spectrum fit to study the Upsilon suppression (mass dependance of energy loss).*

Jets at sPHENIX

- **Unique opportunity to probe the internal jet structure**;
- **Remarkable scaling** of r_c as a function of $p_\perp$ jet;
- Access to the **flavor dependence of the hadronization time**.