Nuclear matter in all these states

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QCD meeting

Proton-proton collisions

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

$$\mathrm{pp} \to \gamma^\star/Z^0 \to \ell^+\ell^- + \mathrm{X} \text{ (Drell-Yan)}$$

Factorization of cross section = approximation

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

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

Proton-nucleus collisions

Cross section in pA collisions assuming collinear factorization

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

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

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

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

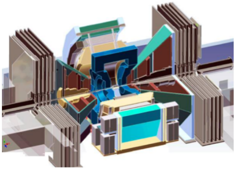
Investigate nuclear effects via:

$$R_{\mathrm{pA}} \equiv \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}\sigma_{\mathrm{pp}}} \approx 1$$

A transitional experiment...

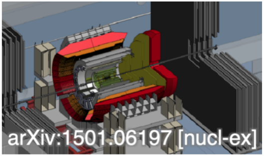
PHENIX

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

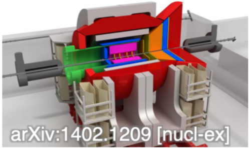


sPHENIX

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

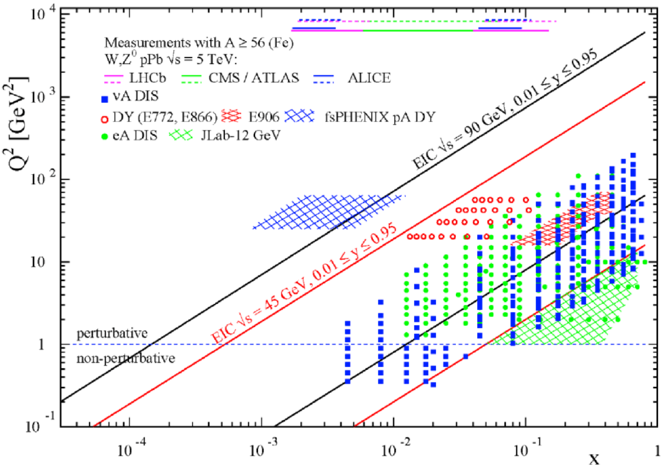


- ep and eA, with several nuclei;
- Transition PHENIX to EIC;
- Large coverage of tracking, calorimetry and PID.



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

Drell-Yan at sPHENIX



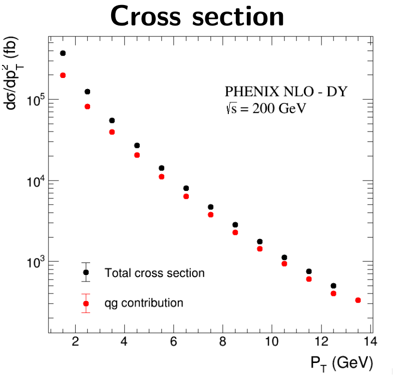
- Forward trackings → **access to small-x**;
- Probe $x \sim 10^{-2}$ to 10^{-3};
- **Complementary measurements from fixed targets to LHC**.

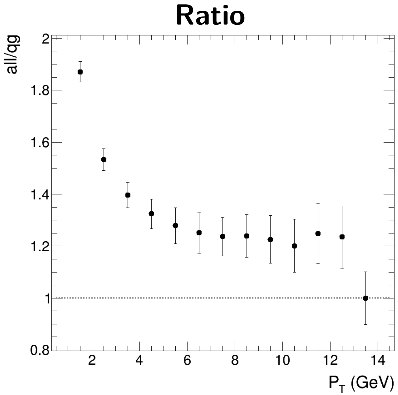
Luminosity expected at sPHENIX

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 (p+p p+Au)**:
  Commissioning and p+p reference data and p+Au cold QCD;
- **2025 (Au+Au)**:
  Large statistics data collection for jets and heavy flavor observables.

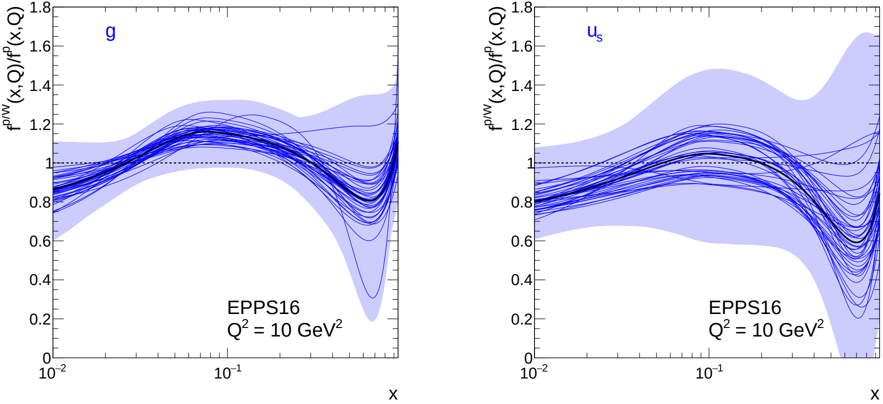
DY at NLO - $\sqrt{s} = 200$ GeV - pp collisions





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

nPDF (EPPS16)



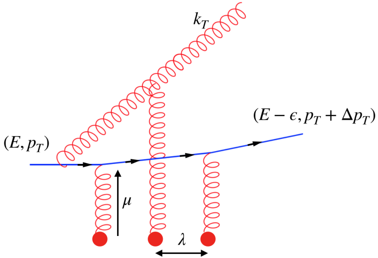
- $\sigma^{\text{DY}} \propto \left(u^{\text{p}} \bar{u}^{\text{A}} + u^{\text{A}} \bar{u}^{\text{p}} \right)$ for $\text{p}_\perp < \text{M}$;
- $\sigma^{\text{DY}} \propto \left(q^{\text{p}} g^{\text{A}} + q^{\text{A}} g^{\text{p}} \right)$ for $4 \lesssim \text{p}_\perp \lesssim 15$ GeV;
- **Huge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

Transport properties of cold nuclear matter

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.



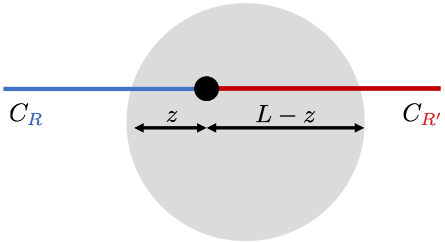
Drell-Yan: a clean probe of the saturation scale I

[Arleo, Naïm, JHEP07(2020)220]

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

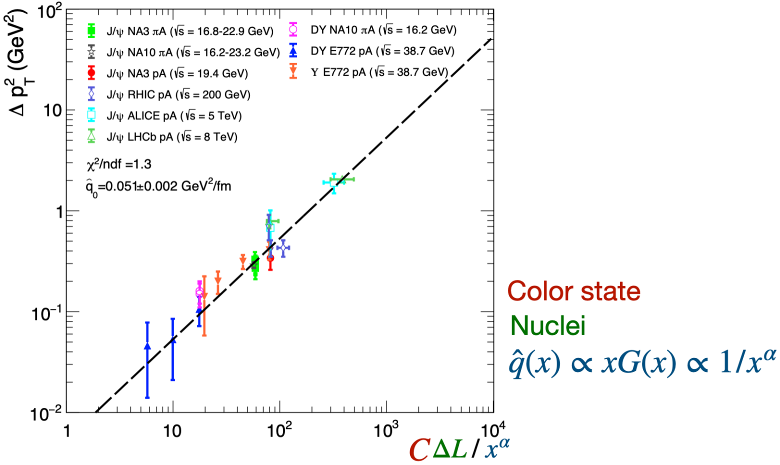
$$\Delta p_\perp^2 = \left\langle p_\perp^2 \right\rangle_{\mathrm{hA}} - \left\langle p_\perp^2 \right\rangle_{\mathrm{hp}} = \frac{C_R + C_{R'}}{2N_c}\left(\hat{q}_{\mathrm{A}} L_{\mathrm{A}} - \hat{q}_{\mathrm{p}} L_{\mathrm{p}}\right)$$

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



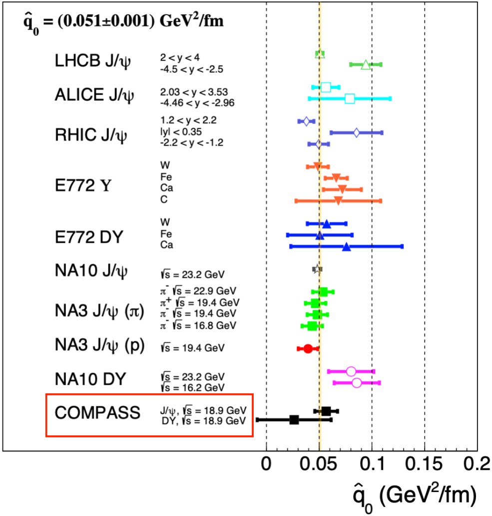
- Drell-Yan: $\mathcal{C}_q + 0 = 4/3$;
- Quarkonia (octet) in pA: $\mathcal{C}_g + \mathcal{C}_{[Q\bar{Q}]_8} = 3 + 3$.

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



- 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.

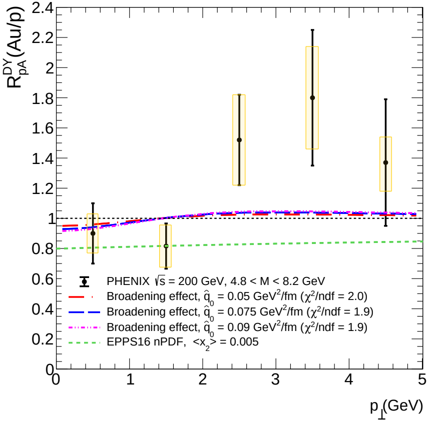
Extraction of the transport coefficient



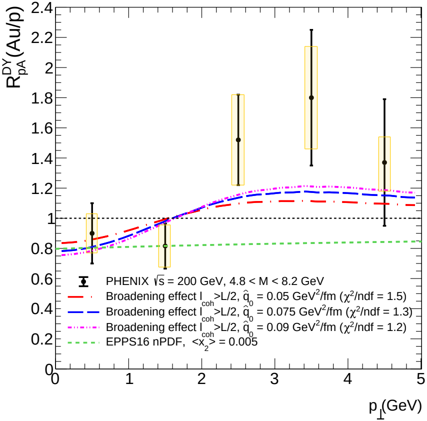
- New (strong?) constraint from Drell-Yan data at sPHENIX.

Drell-Yan at PHENIX experiment - $\sqrt{s} = 200$ GeV

$<L^{DY}> = L^A/2$



$<L^{DY}> = L^A$



- Probe the coherence lenght between low and high energy picture;
- Need to have better statistics to conclude.

Drell-Yan analysis at sPHENIX

Processes:

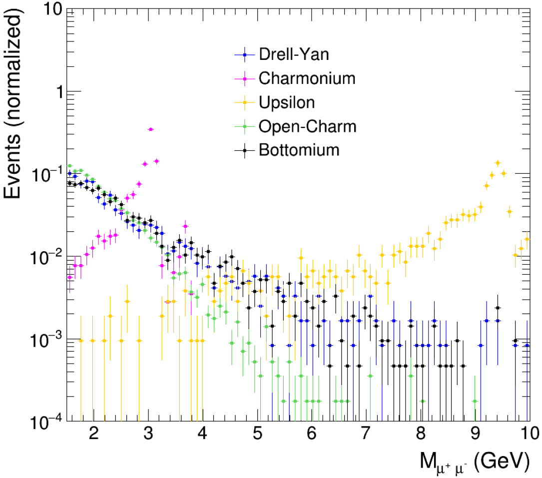
- Charmonium (J/ψ, ψ')
- Bottomonium (Υ)
- Open-Charm (D mesons)
- Bottom (B mesons)
- **Drell-Yan**

Procedure:

- **Simulate all QCD processes** in sPHENIX softwares and identify the contribution of each other in HMDY region;
- **Fit the mass spectrum** with the following function:

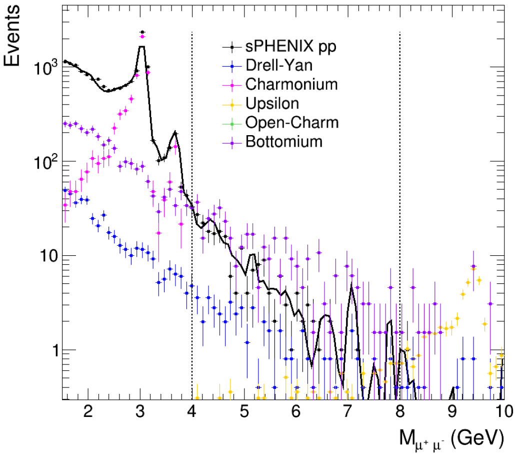
$$\mathrm{f(M)}_{\mathrm{fit}} = \alpha_1 f(M)^{\mathsf{Charmonium}}_{\mathrm{MC}} + \alpha_2 f(M)^{\mathsf{DY}}_{\mathrm{MC}} + \alpha_3 f(M)^{\mathrm{OC}}_{\mathrm{MC}} + \alpha_4 f(M)^{\mathrm{Bottom}}_{\mathrm{MC}} + \alpha_5 f(M)^{\mathsf{Bottomium}}_{\mathrm{MC}}$$

Simulation by using sPHENIX software



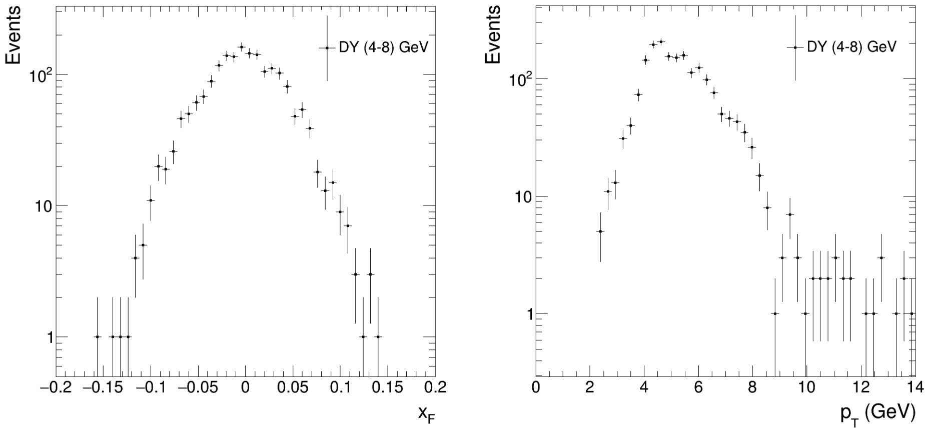
- **Very close shape** from DY, Bottomium and OC contributions;
- Bottom is **less steeper** compared to OC, especially at M $\gtrsim$ 4 GeV;
- **Tail from charmonium/bottomium at low mass**: QED radiation.

Invariant mass reconstruction



- **Improve the stat**. (according to sPHENIX luminosity): in progress;
- Not enough data to constrain large mass, cross section low;
- $\sigma_{\rm OC} > \sigma_{\rm Bottom} > \sigma_{\rm DY}$ at M $\sim$ 2 GeV.

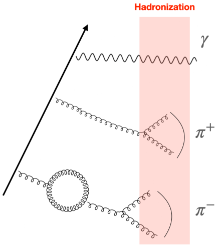
Drell-Yan - Kinematic phase space



- 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

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

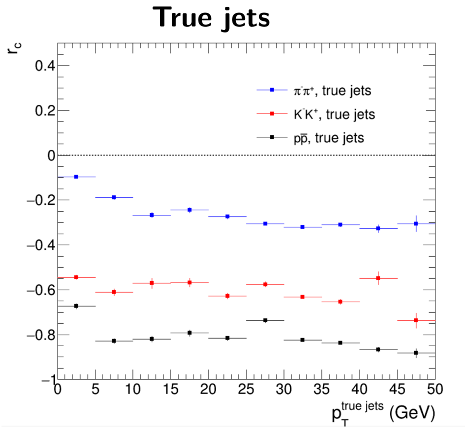


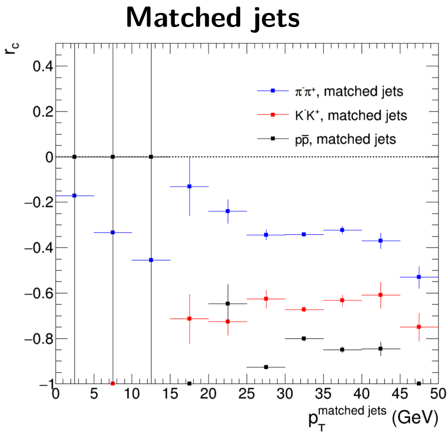
Observable:

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

where h1,h2 $\in (\pi^{\pm}, K^{\pm}, p)$

Jet structure at sPHENIX II





- Significant differences in r_c observed for various flavor combinations.

Conclusion

Drell-Yan at sPHENIX

- Background extraction depends on the mastery of Open-Charm and Open-Bottom contributions;
- Clean process to study cold nuclear matter effects (gluon nPDF, boadening, saturations scale).

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

Internal jet structure at sPHENIX

- Significant differences in r_c observed for various flavor combinations;
- Possible to check the formation time calculation;
- Essential to have a good PID for the flavor-tagged measurements (EIC).