Dubna@2016.11.01

Electromagnetic Radiation in Hot QCD Matter

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in collaboration with

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PRC 90, 025204 (2014) & arXiv:1610.06213

Contents

- **Motivation**
- EM radiation from hadronic gas
- Direct Photon Elliptic Flow at RHIC & LHC
- Conclusion

RAON

a pure Korean word meaning Delightful, Joyful, Happy, …

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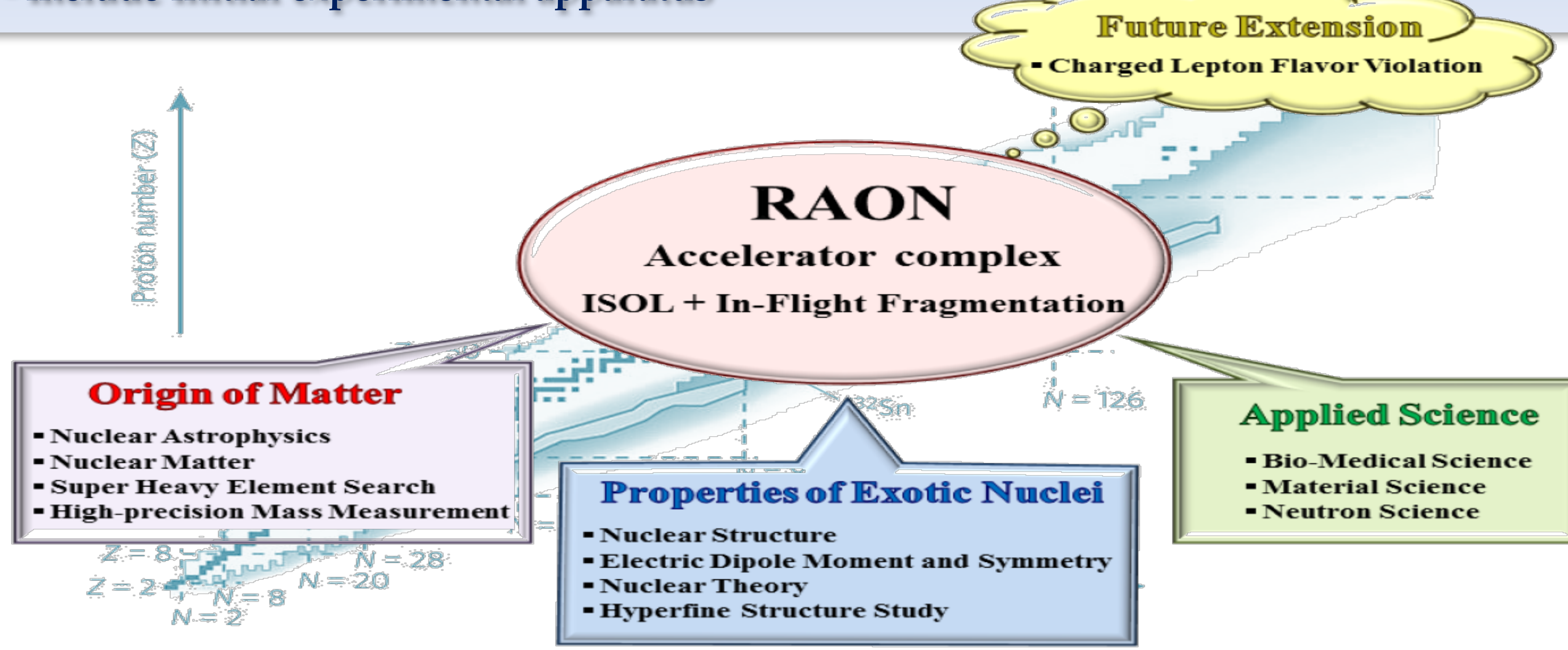
in 2011, Korean government approved a **Rare Isotope Accelerator Project**

Location

Jilin
Jilin
Fushun
Shenyang
Tong Hua
Anshan
Dalian
Pyongyang
북한
Seoul
Incheon
Qingdao
Dae-Jeon
Daejeon
대한민국
Daegu
Kwangju
Busan
Cheju do
Fukuoka
Hiroshima
세토내해
Awaji-shima
Okayama
Kobe
Kyoto
Nagoya
Yokohama
일본
Shikoku
Nanjing
© 2008 ZENRIN
Image NASA
© 2008 Europa Technologies
© 2008 NGIS
©2008 Google
38°21'36.92" N 128°35'27.44" E
내려다보는 높이 1614.16 km
952,066m²
Supply/Test/Office Bldg
Exp. Halls
IF Target
ISOL
Preserved Forest Area
Driver SC Linac
Post Accelerator
Injector
Control Center
Exp. Halls
SRF Facility
Bird's-eye view

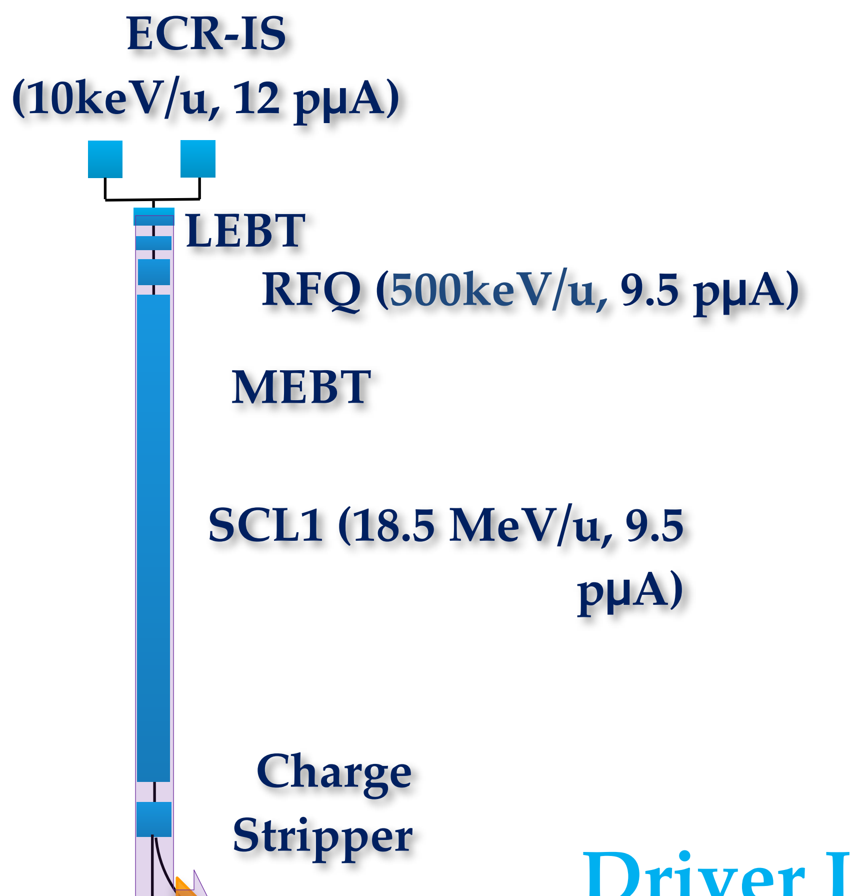
Rare Isotope Science Project (RISP)

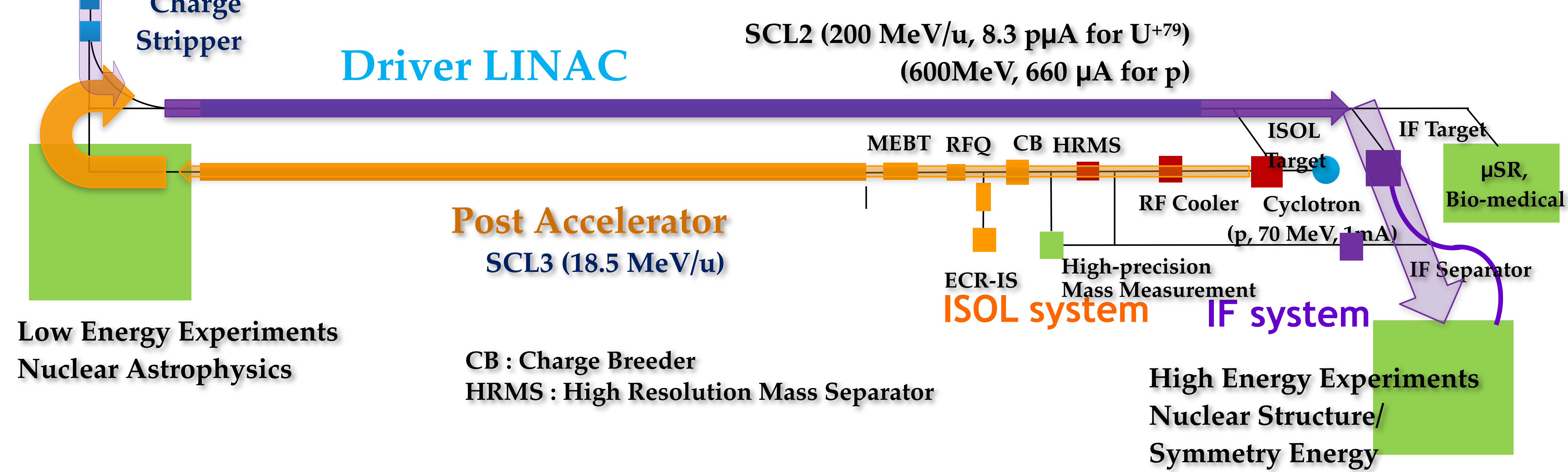
- Goal : To build a heavy ion accelerator complex RAON
  for rare isotope science researches in Korea
- Project period : 2011.12 - 2021.12
- Total Budget : ~$ 1.43 billion
  (Facilities ~ $ 0.46 bill., Bldgs & Utilities ~ $ 0.97 bill.)
  - include initial experimental apparatus



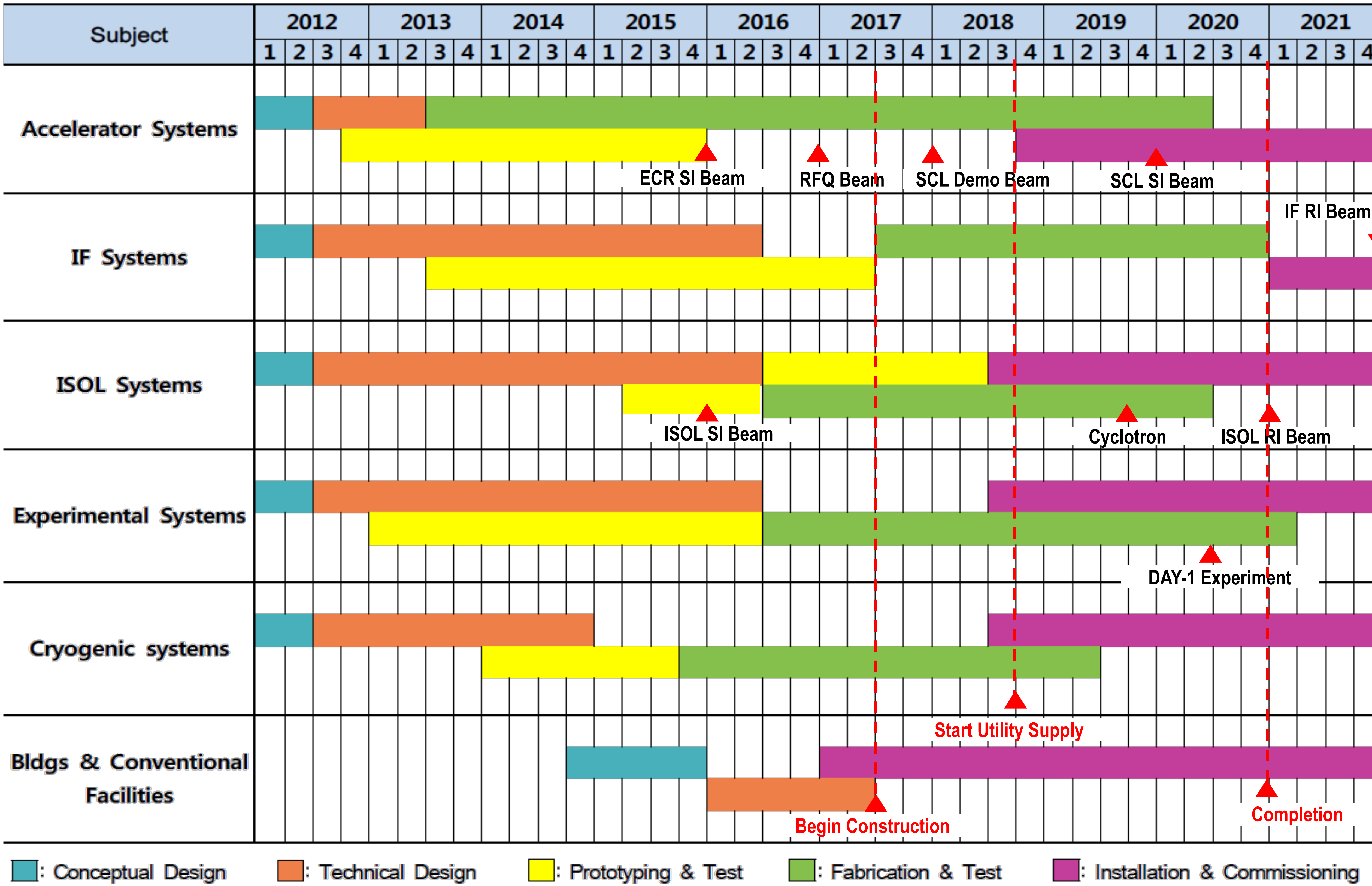
RAON Concept

- ❑ High intensity RI beams by ISOL & IF
  - ISOL : direct fission of ^{238}U by 70MeV protons
  - IF : 200MeV/u, 8.3pμA of ^{238}U
- ❑ High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to ~10^8 pps
- ❑ More exotic RI beams by ISOL+IF





RISP Milestones and Schedule



My recent works have been related to neutron stars
- NS EoS / Dense Matter
- NS Binary Evolution / Gravitational Waves

for RAON

better to start from where you have an advantage

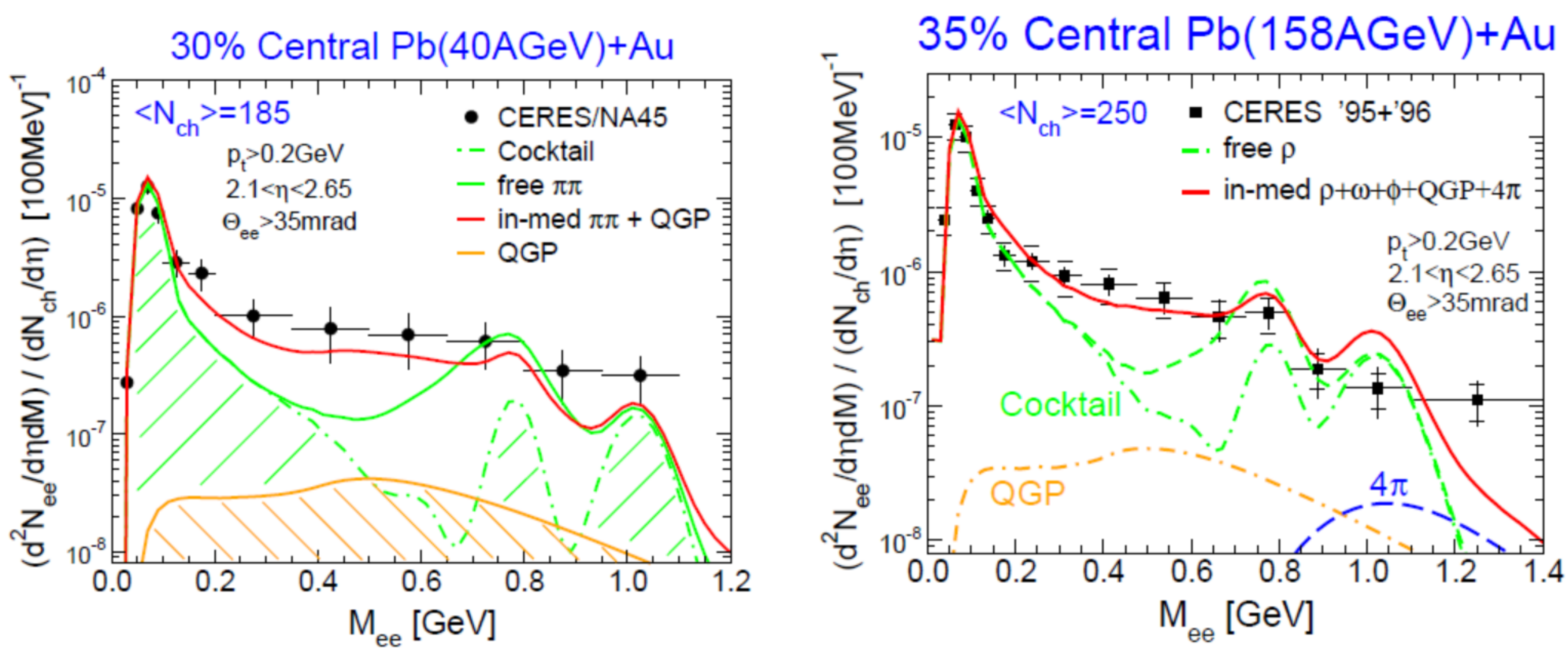
Some experience on Heavy Ion Collisions at Stony Brook
- Lee, Wirstam, Zahed, Hansson, PLB 448, 168 (1999)
- Lee, Yamagishi, Zahed, PRC 58, 2899 (1998)
- Lee, Yamagishi, Zahed, NPA 653, 185 (1999)

Why Photons & Dileptons ?

- No strong interaction
- Can provide direct information on dense medium
- Right time to revisit

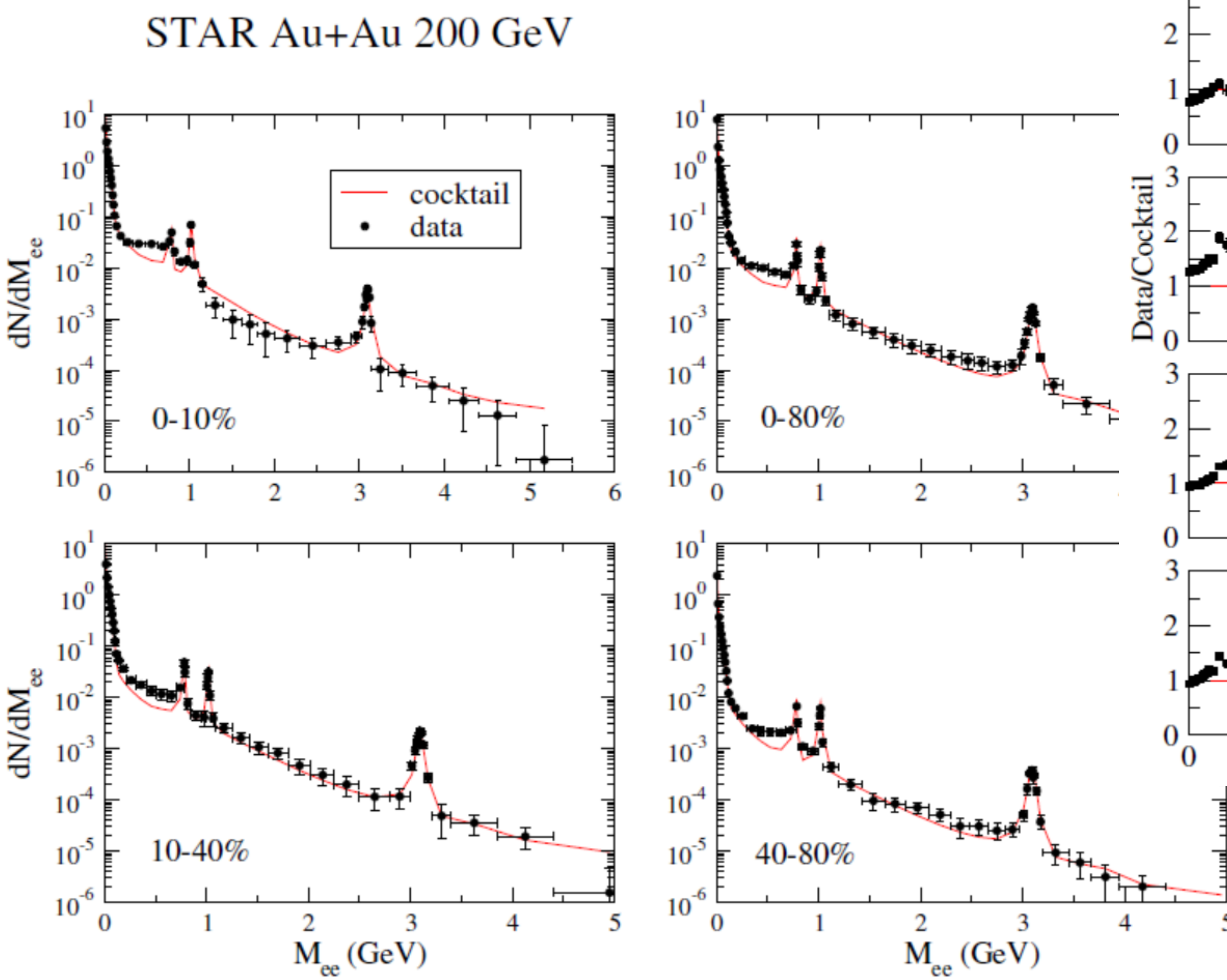
CERES/NA45 Pb+Au 8.8 & 17.3 GeV

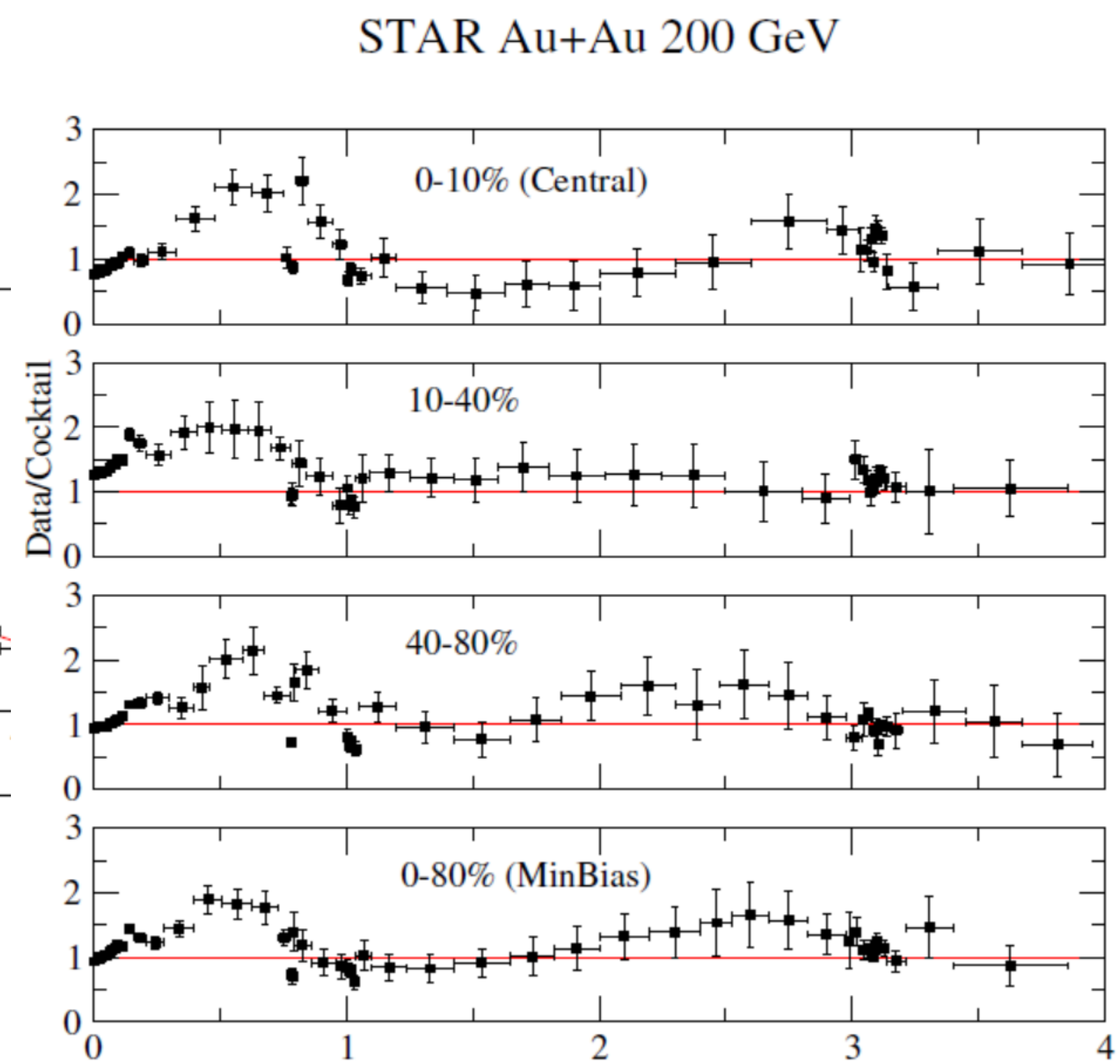
R.Rapp, arXiv:1306.6394



Key question : low-mass dilepton enhancement

STAR Dilepton Enhancement Au+Au 200 GeV

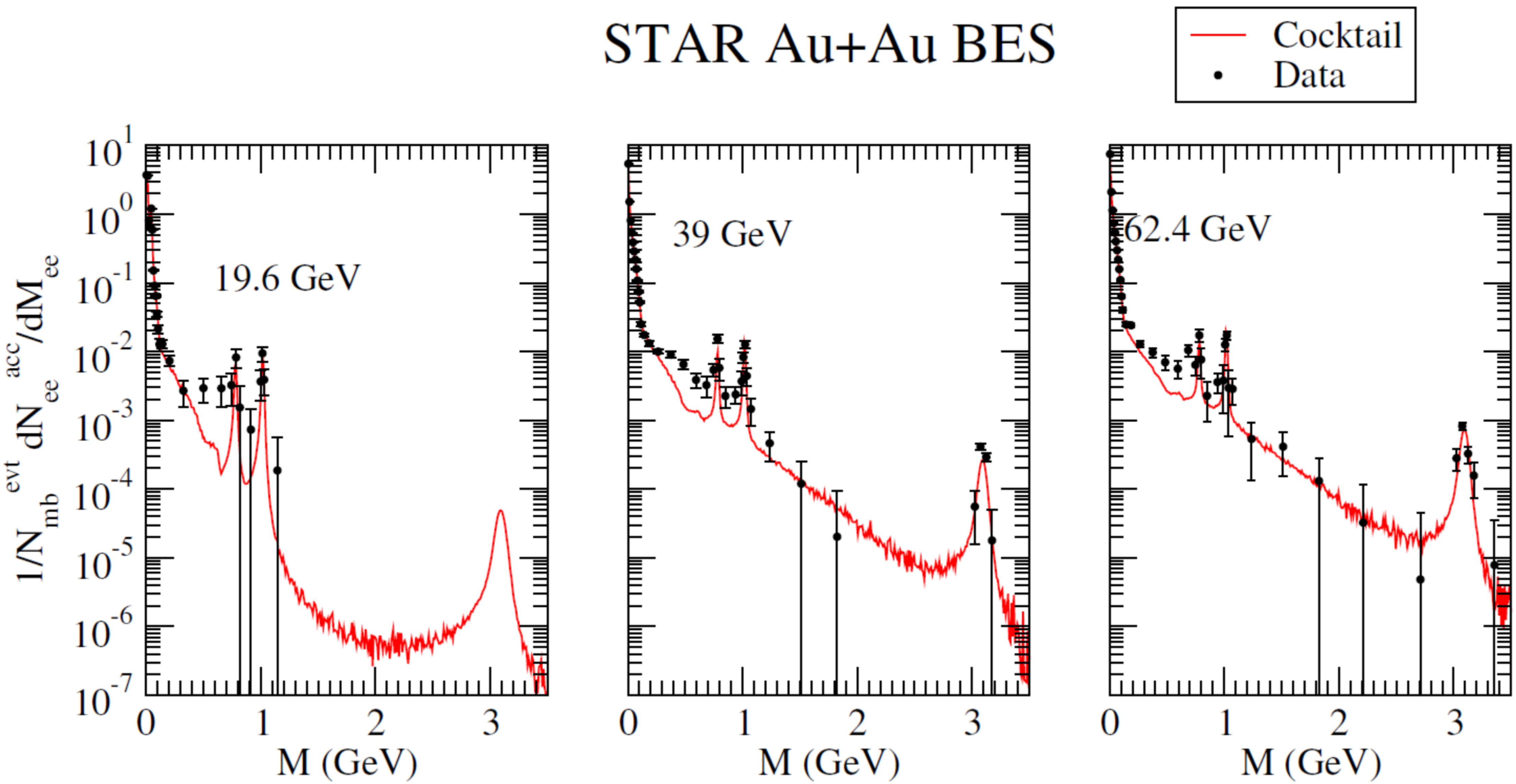




arXiv:1305.5447

STAR Beam Energy Scan

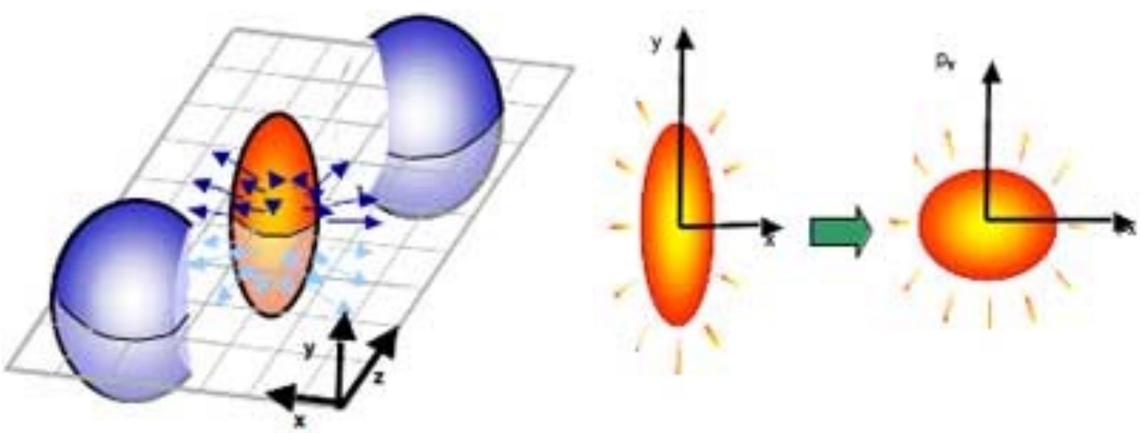
arXiv:1305.5447

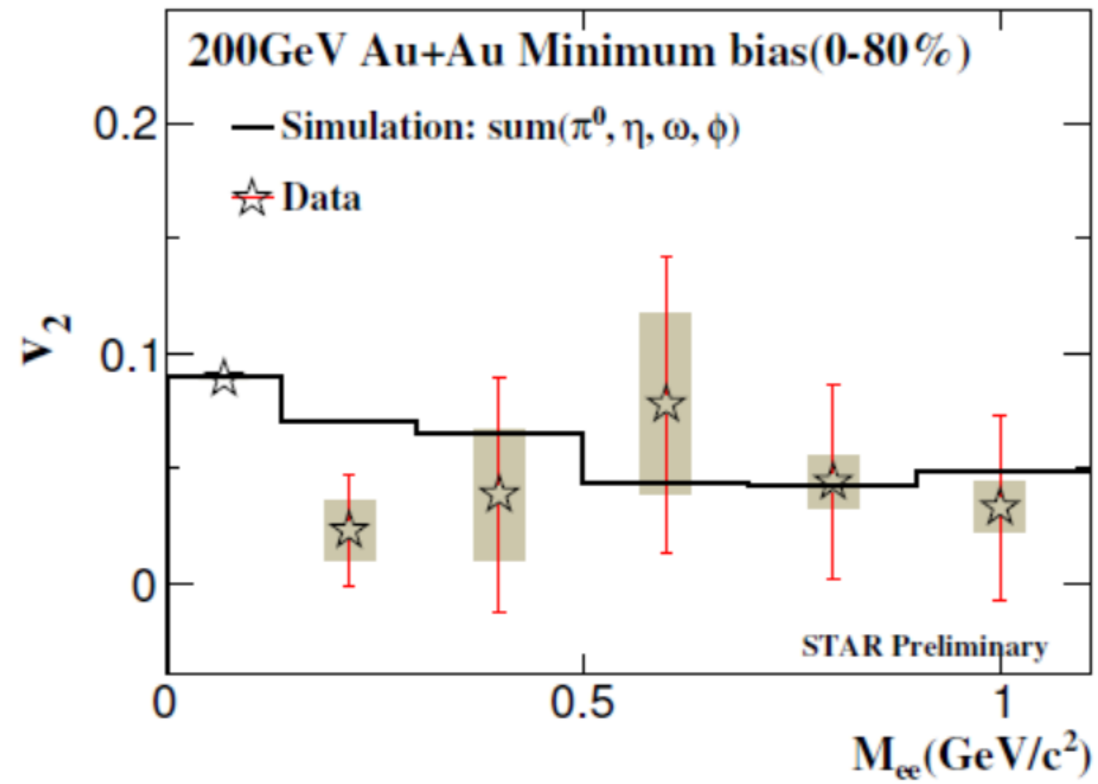


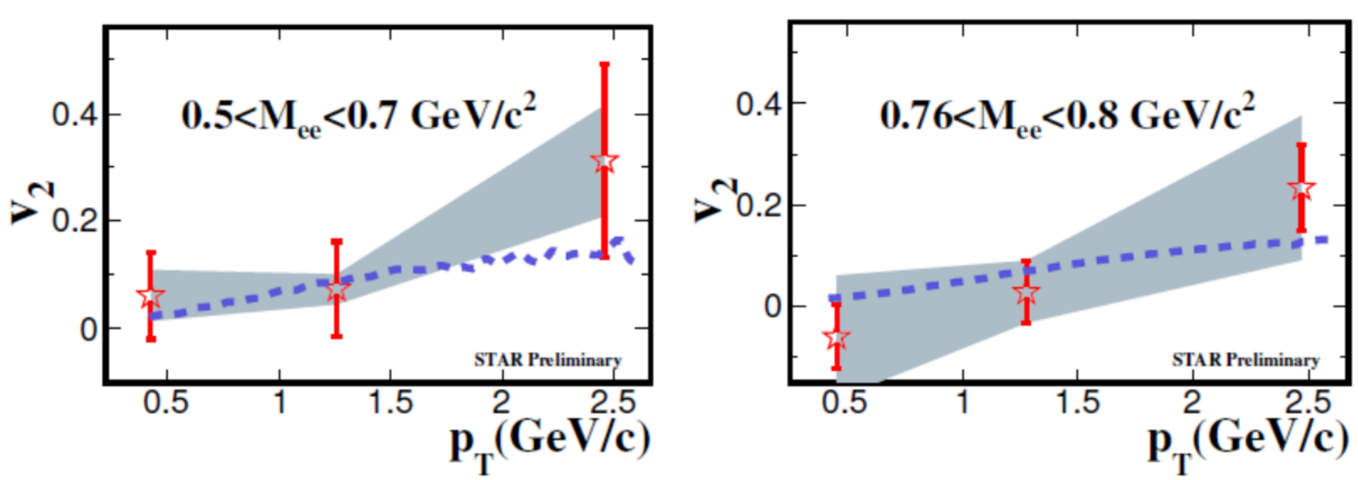
STAR Au+Au 200 GeV

arXiv:1305.5447

Elliptic Flow



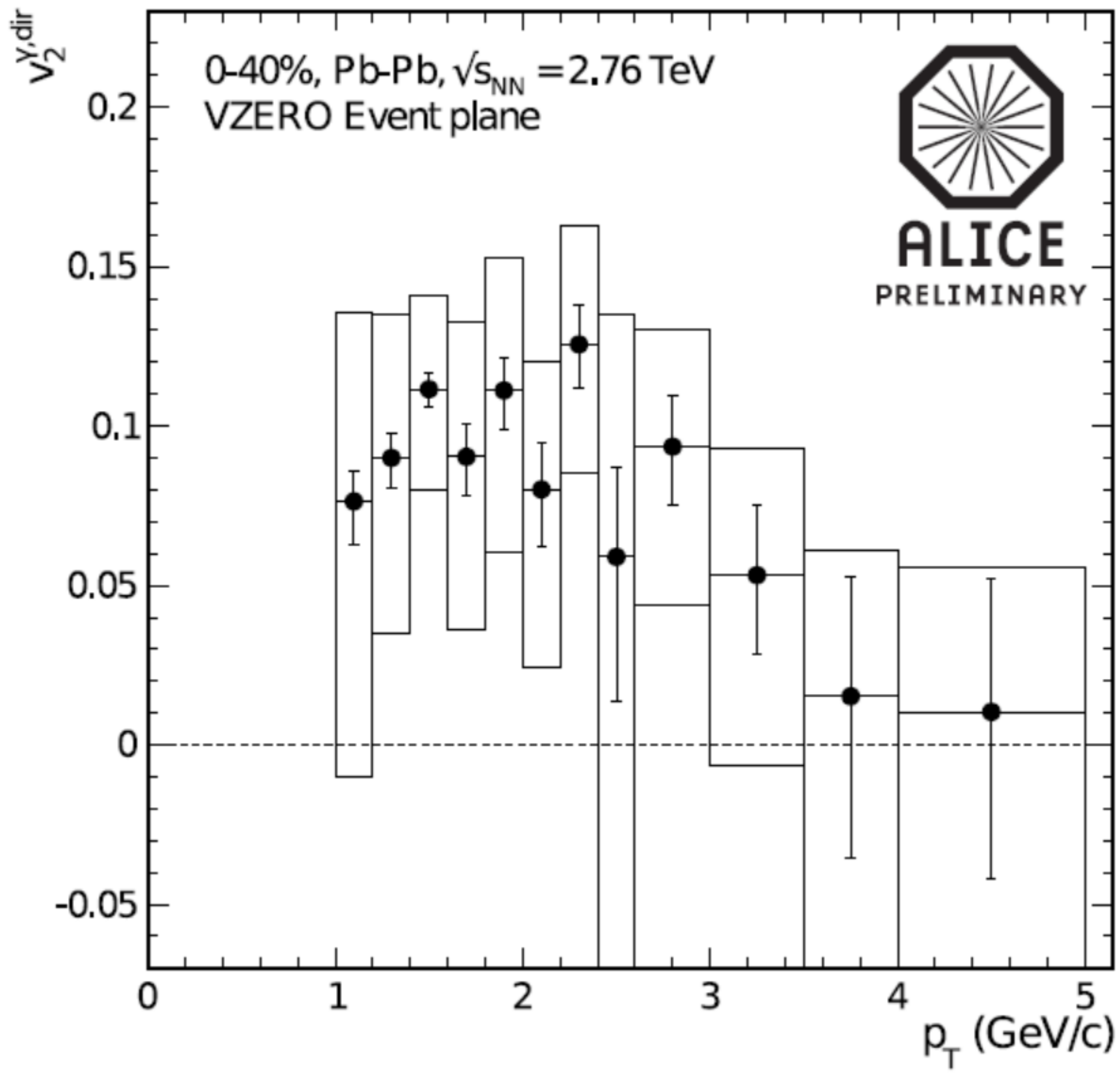




ALICE Pb+Pb 2.76 TeV

arXiv:1212.3995

Elliptic Flow



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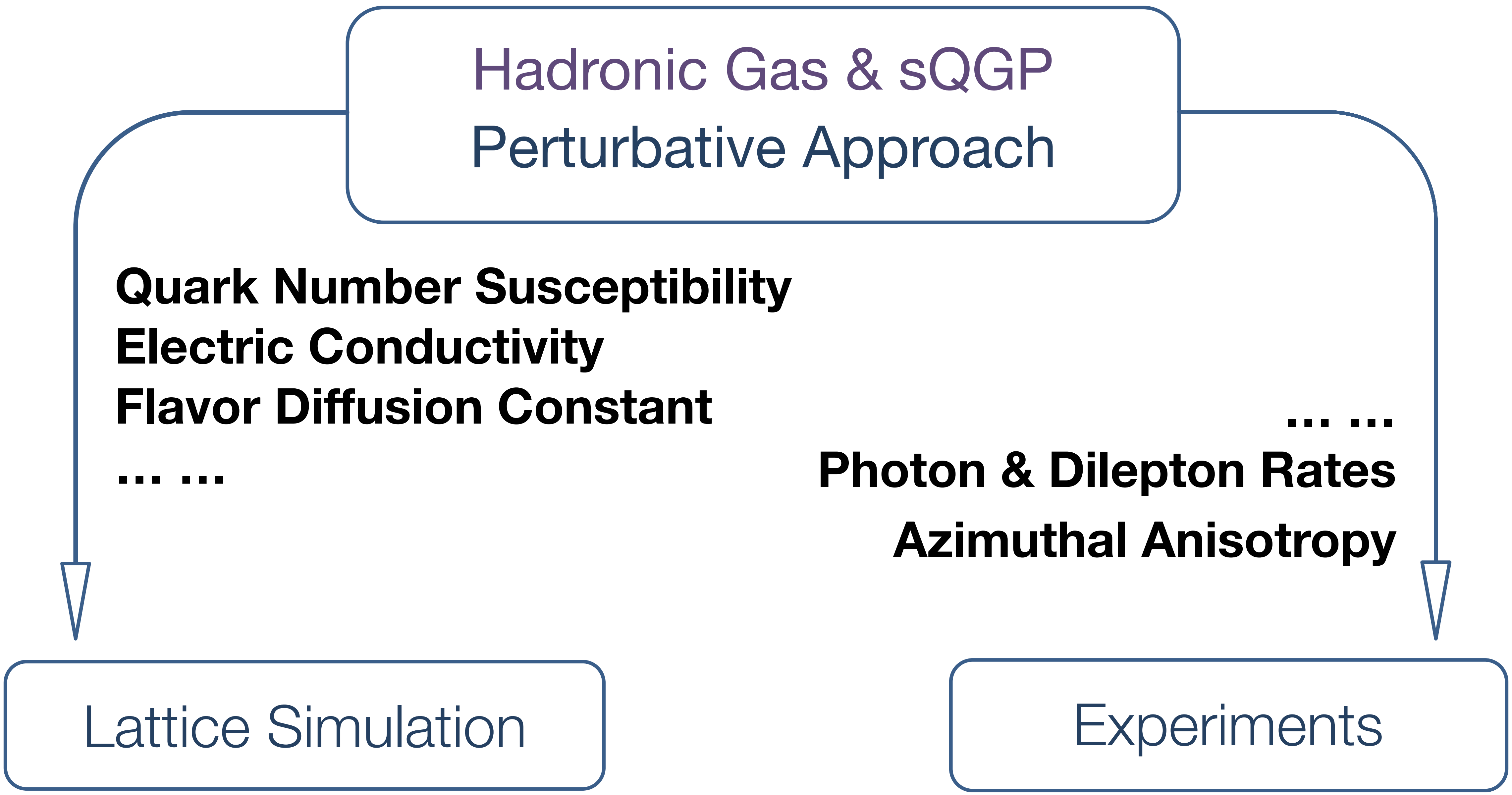
Theory vs Experiment



Rates, Hydro Evolution, Detector Acceptance

Elliptic Flow, in this talk

$v_2(M)$ $v_2(p_T)$

$\frac{dN}{dM}$

Detector Acceptance

$$\frac{d^4N}{M\,dM\,q_T dq_T\,dy\,d\phi}(M, q_T, y, \phi) = \mathbf{DetAcc}(M, q_T, y, \phi) \times \int_{\tau_0}^{\tau_{f,o}} \tau d\tau \int_{-\infty}^{\infty} d\eta \int_0^{r_{\max}} r dr \int_0^{2\pi} d\theta$$
$$\times \left[\frac{dR}{d^4q}(q; T, \mu_B, \mu_\pi) \otimes \mathbf{Hydro}(T, \mu_B, \mu_\pi; \tau, \eta, r, \theta)\right]$$

$\frac{dN}{dp_T}$

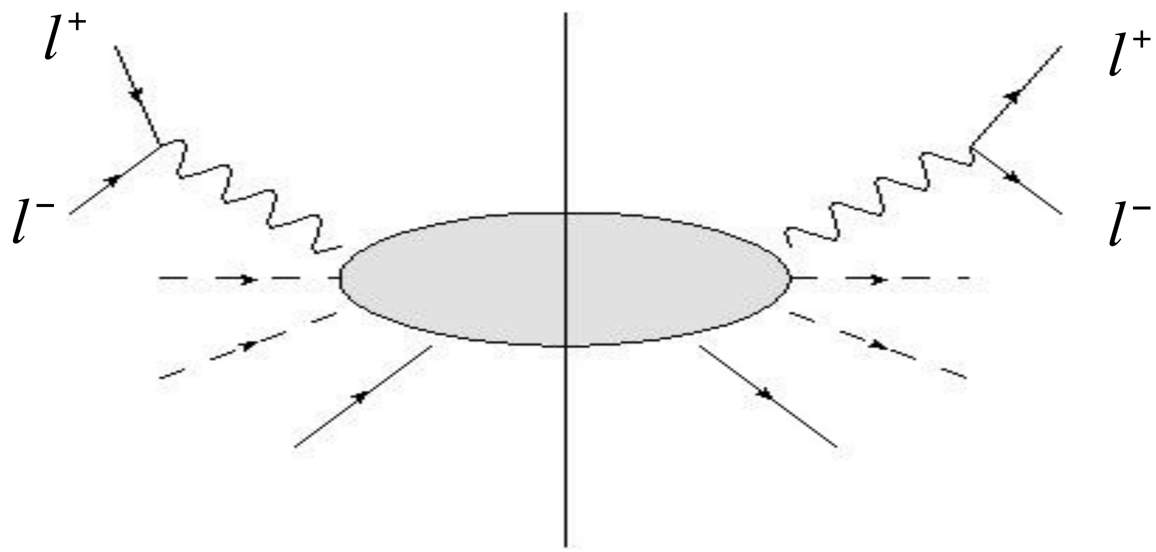
$\frac{dN}{dM\,d\eta}$

Hydro Evolution

$$\frac{dR}{d^4q} \equiv \frac{dN}{d^4q d^4x}$$

EM Rates, in this talk

Dilepton rates from correlation functions

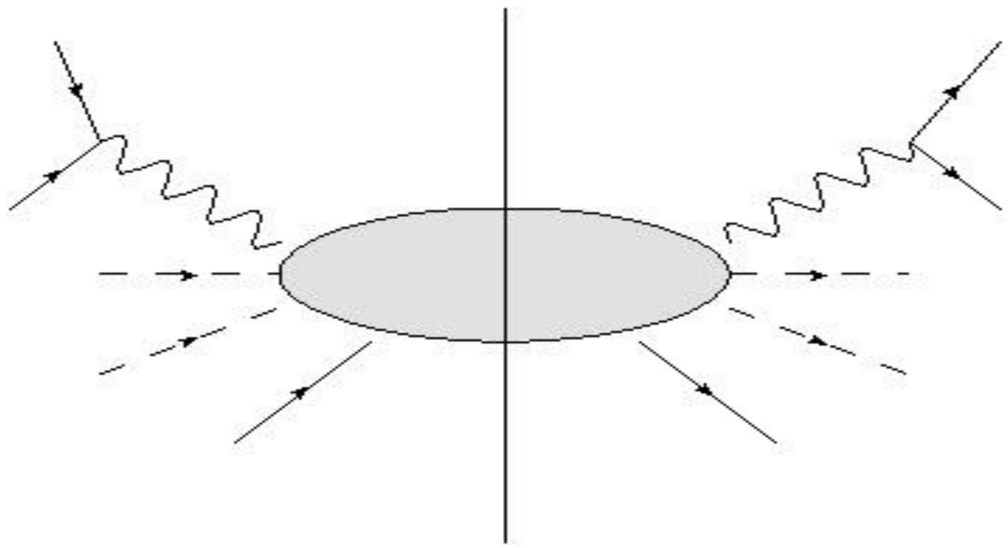


$$\frac{dR}{d^4q} = \frac{-\alpha^2}{6\pi^3 q^2}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}\mathbf{W}(q)$$

$$\mathbf{W}(q) = \int d^4x e^{-iq\cdot x}\mathrm{Tr}\left[e^{-(\mathbf{H}-\mathbf{F})/T}\,\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)\right]$$

$$\mathbf{J}_\mu(x) = \sum_f \tilde{e}_f\,\overline{\mathbf{q}}_f\gamma_\mu\mathbf{q}_f(x)$$

Direct & Virtual Photon Rates



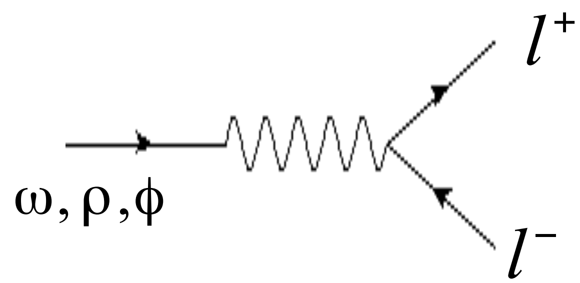
$$\frac{q^0 dN}{d^3q} = -\frac{\alpha}{4\pi^2}\mathbf{W}(q)$$

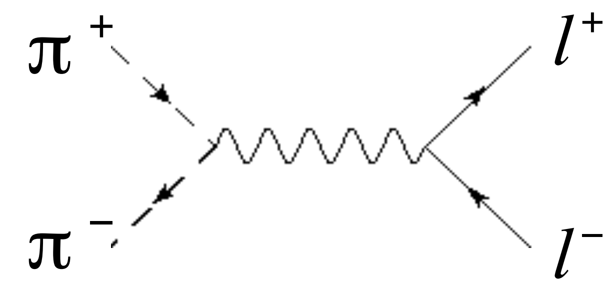
$$M \to 0,\ N^* \approx N$$

$$\frac{dR}{d^4q} = \frac{2\alpha}{3\pi M^2}\left(1 + \frac{2m_l^2}{M^2}\right)\left(1 - \frac{4m_l^2}{M^2}\right)^{1/2}\left(\frac{q^0 dN^*}{d^3q}\right)$$

Dilepton rates from hadronic gas

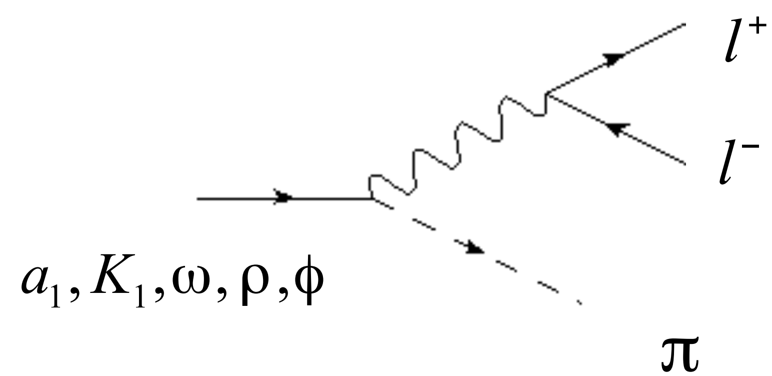
$$i\int d^4x\; e^{iq\cdot x}\left\langle 0\left|T^* J^\mu(x) J_\mu(0)\right|0\right\rangle$$





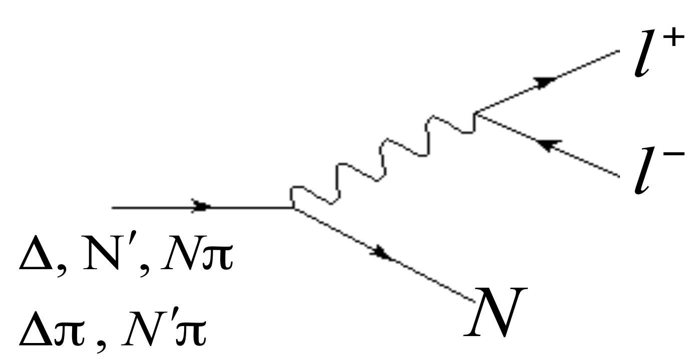
+ ...

$$+\sum_a i\int d\pi \int d^4x\; e^{iq\cdot x}\left\langle \pi^a_{in}(k)\left|T^* J^\mu(x) J_\mu(0)\right|\pi^a_{in}(k)\right\rangle$$



+ ...

$$+\sum_{s,I} i\int dN \int d^4x\; e^{iq\cdot x}\left\langle N^{s,I}_{in}(k)\left|T^* J^\mu(x) J_\mu(0)\right|N^{s,I}_{in}(k)\right\rangle$$



+ ...

Pionic Gas

$$\mathbf{W}^F(q) = \mathbf{W}_0^F(q) + \frac{1}{f_\pi^2}\int d\pi \mathbf{W}_\pi^F(q,k) + \frac{1}{2!}\frac{1}{f_\pi^4}\int d\pi_1 d\pi_2 \mathbf{W}_{\pi\pi}^F(q,k_1,k_2) + \cdots$$

$$\int d\pi = \int \frac{d^3k}{(2\pi)^3}\frac{n(E-\mu_\pi)}{2E}$$

$$\begin{aligned}
\mathbf{W}_0^F(q) &= i\int d^4x e^{iq\cdot x}\langle 0|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|0\rangle \\
\mathbf{W}_\pi^F(q,k) &= i f_\pi^2\int d^4x e^{iq\cdot x}\langle \pi^a(k)|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|\pi^a(k)\rangle \\
\mathbf{W}_{\pi\pi}^F(q,k_1,k_2) &= i f_\pi^4\int d^4x e^{iq\cdot x}\langle \pi^a(k_1)\pi^b(k_2)|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|\pi^a(k_1)\pi^b(k_2)\rangle
\end{aligned}$$

Vector & Axial Correlators, Spectral Functions

Steele, Yamagishi, Zahed, PLB (1996) : SU(2)
Lee, Yamagishi, Zahed, PRC (1998) : SU(3)

$$\mathbf{J}_\mu = \bar{q}\gamma_\mu Q^{\rm em} q = \mathbf{V}_\mu^3 + \frac{1}{\sqrt{3}}\mathbf{V}_\mu^8$$

$$\mathrm{Im}\left(i\int_y e^{-iq\cdot y}\langle 0|T^*(\mathbf{V}_\mu^c(y)\mathbf{V}_\nu^d(0)|0\rangle\right) = \left(-q^2 g_{\mu\nu} + q_\nu q_\nu\right)\mathrm{Im}\mathbf{\Pi}_V^{cd}(q^2)$$

$$\mathrm{Im}\left(i\int_y e^{-iq\cdot y}\langle 0|T^*(\mathbf{j}_{A,\mu}^c(y)\mathbf{j}_{A,\nu}^d(0)|0\rangle\right) = \left(-q^2 g_{\mu\nu} + q_\nu q_\nu\right)\mathrm{Im}\mathbf{\Pi}_A^{cd}(q^2)$$

		$I^G(J^{PC})$	Mass (m_i)	Decay width (G_i)	Decay constant (f_i)
Π_V^I	$\rho(770)$	$1^+(1^{--})$	768.5	150.7	130.67
	$\rho(1450)$		1465	310	106.69
	$\rho(1700)$		1700	235	75.44
Π_V^Y	$\omega(782)$	$0^-(1^{--})$	781.94	8.43	46
	$\omega(1420)$		1419	174	46
	$\omega(1600)$		1649	220	46
	$\phi(1020)$	$0^-(1^{--})$	1020	4.43	79
	$\phi(1680)$		1680	150	79
Π_A^I	$a_1(1260)$	$1^-(1^{++})$	1230	400	190 (f_ρ)
Π_A^{UV}	$K_1(1270)$	$\frac{1}{2}(1^+)$	1273	90	90
	$K_1(1400)$		1402	174	90

$\Pi_V^I \equiv \Pi_V^{33}$

$\Pi_V^Y \equiv \frac{4}{3}\Pi_V^{88}$

Spectral Functions

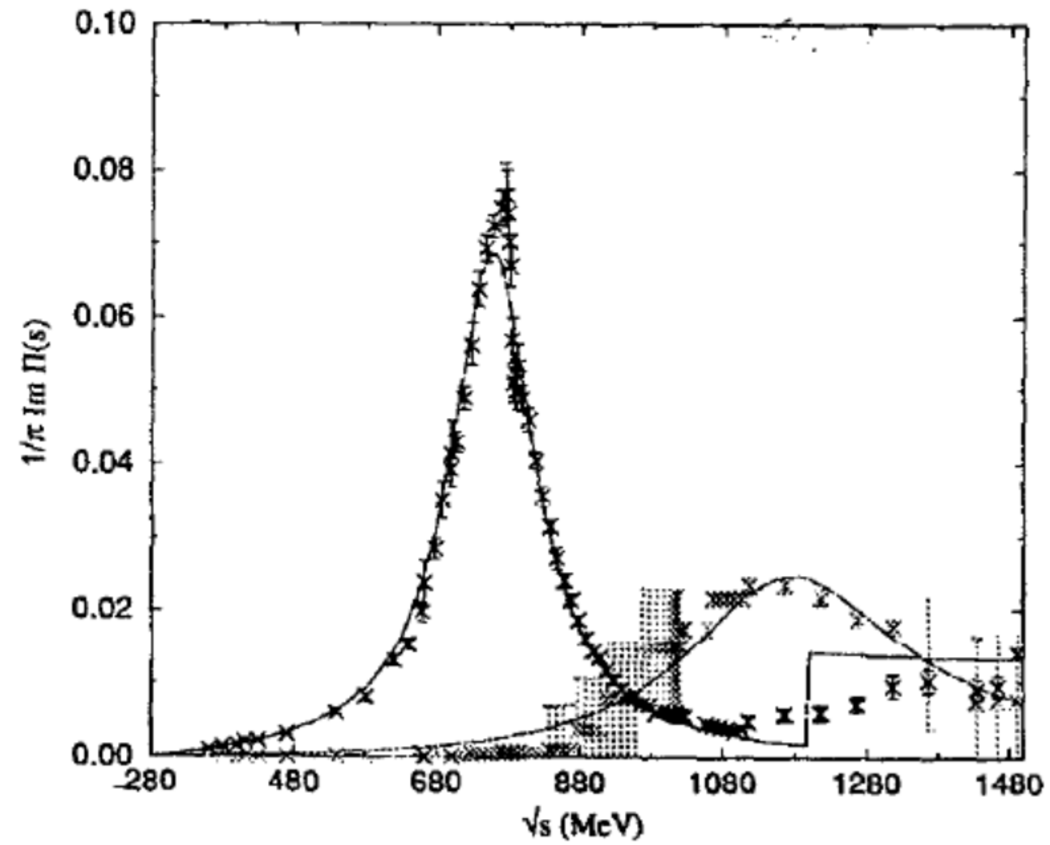
Steele, Yamagishi, Zahed, PLB (1996) : SU(2)
Lee, Yamagishi, Zahed, PRC (1998) : SU(3)

$$\Pi_V^I(q^2) = \frac{f_\rho^2}{q^2}\,\frac{m_\rho^2 + \gamma q^2}{m_\rho^2 - q^2 - i m_\rho \Gamma_\rho(q^2)}$$

$$\Pi_A^I(q^2) = \frac{f_{a_1}^2}{m_{a_1}^2 - q^2 - i m_{a_1}\Gamma_{a_1}(q^2)}$$

$$\Gamma_\rho(q^2) = \theta(q^2 - 4m_\pi^2)\,\Gamma_{0,\rho}\,\frac{m_\rho}{\sqrt{q^2}}\left(\frac{q^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2}\right)^{3/2}$$

$$\Gamma_{a_1}(q^2) = \theta(q^2 - 9m_\pi^2)\,\Gamma_{0,a_1}\,\frac{m_{a_1}}{\sqrt{q^2}}\left(\frac{q^2 - 9m_\pi^2}{m_{a_1}^2 - 9m_\pi^2}\right)^{3/2}$$



Mixing between vector & axial

$$\begin{aligned}\mathrm{Im}\mathbf{W}^F_\pi(q,k) &= 12\,q^2\,\mathrm{Im}\mathbf{\Pi}_V(q^2)\\ &- 6\,(k+q)^2\mathrm{Im}\mathbf{\Pi}_A\left((k+q)^2\right) + (q\to -q)\\ &+ 8\left((k\cdot q)^2 - m_\pi^2 q^2\right)\mathrm{Im}\mathbf{\Pi}_V(q^2)\times \mathrm{Re}\Delta_R(k+q) + (q\to -q)\end{aligned}$$

$k \to 0$

$m_\pi \to 0$

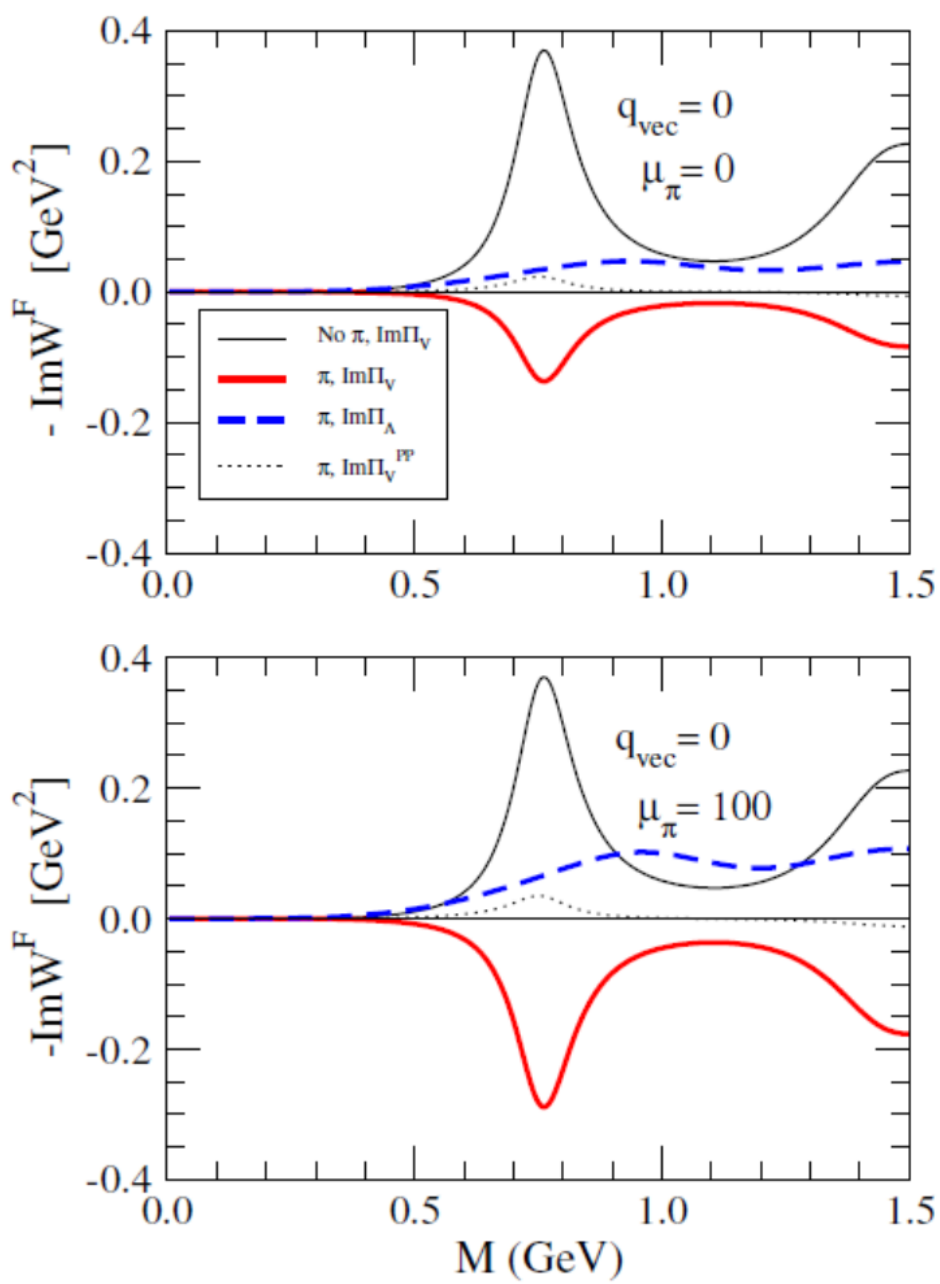
naive limit upto one pion

$$\mathrm{Im}\mathbf{W}^F(q) \approx -3\,q^2\left[(1-4\kappa)\,\mathrm{Im}\mathbf{\Pi}_V(q^2) + 4\kappa\,\mathrm{Im}\mathbf{\Pi}_A(q^2)\right]$$

$$\kappa = \frac{1}{f_\pi^2}\int d\pi$$

decrease *increase*

Mixing between vector-axial : Chiral symmetry restoration



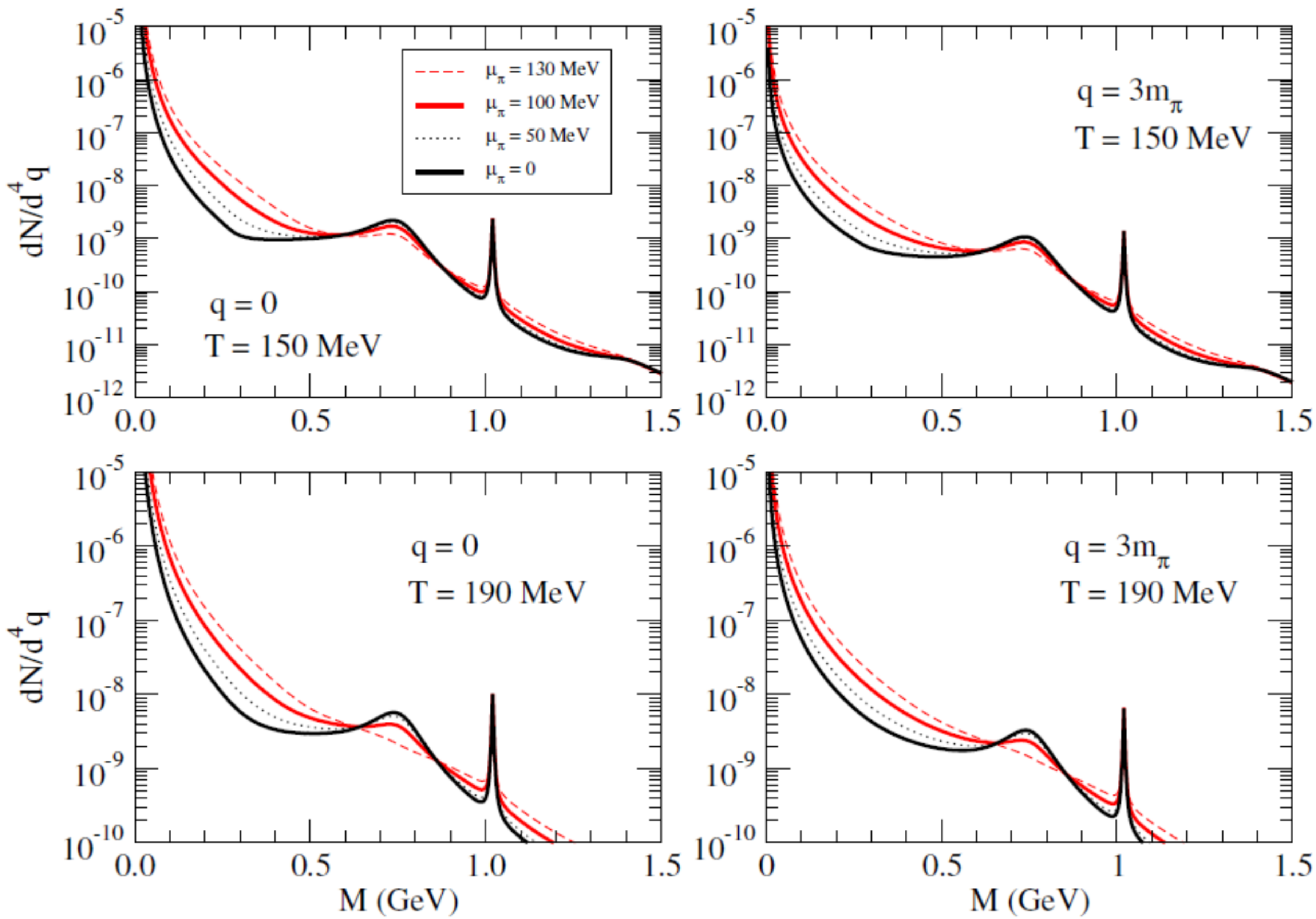
As pion chemical potential increase

- **Reduction of Vector Contribution**
  due to the cancellation
  (no pion + pion contribution)
- **Enhancement of Axial Contribution**

Lee & Zahed PRC 90, 025204 (2014)

Dilepton Rates up to two pion

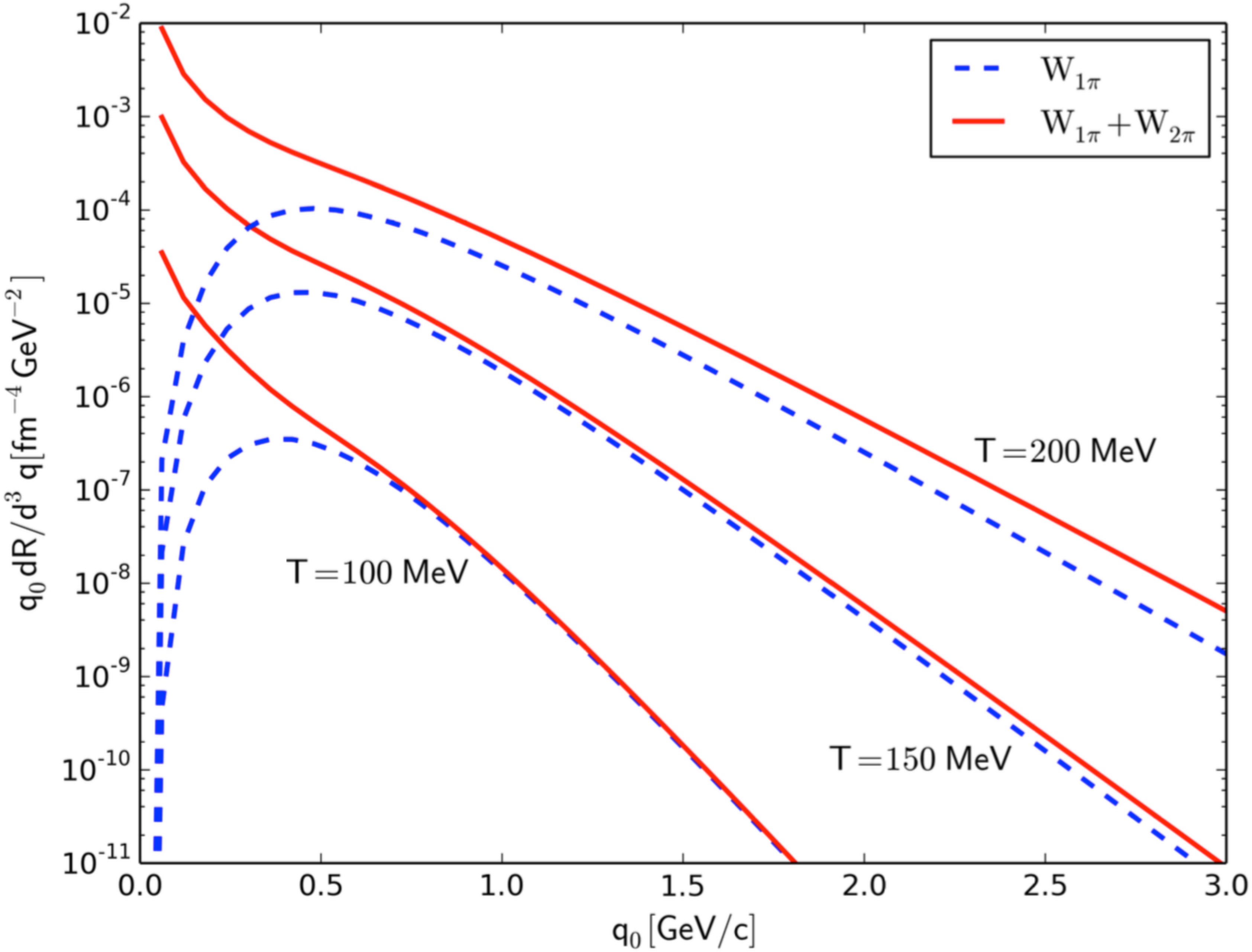
Low-mass enhancement due to mixing between vector & axial



Lee & Zahed PRC 90, 025204 (2014)

Photon emission rates from hadronic gas

arXiv:1610.06213



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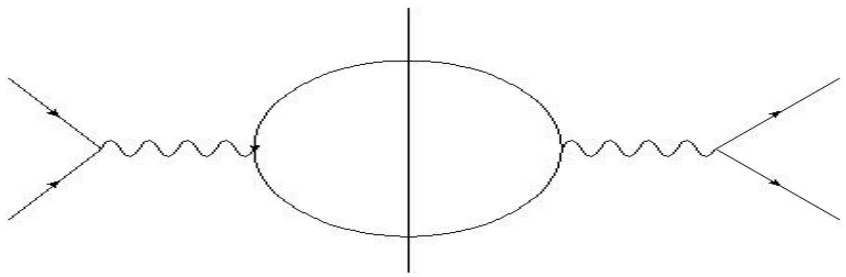
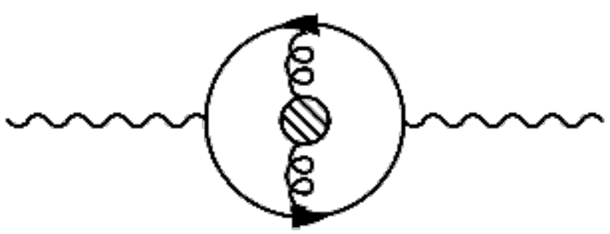
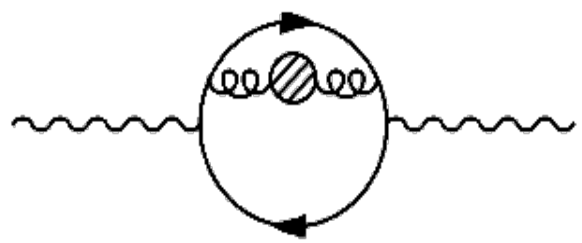
sQGP strongly-interacting QGP

PLB 448, 168 (1999)



$$\mathrm{Im}\,\mathbf{W}_0^R(q) = \frac{N_c\tilde{\mathbf{e}}^2}{4\pi}\,q^2\left[1+\frac{2T}{|\vec{q}|}\ln\left(\frac{n_+}{n_-}\right)\right]$$





$$n_\pm = \frac{1}{e^{(q_0\pm|\vec{q}|)/2T}+1}$$

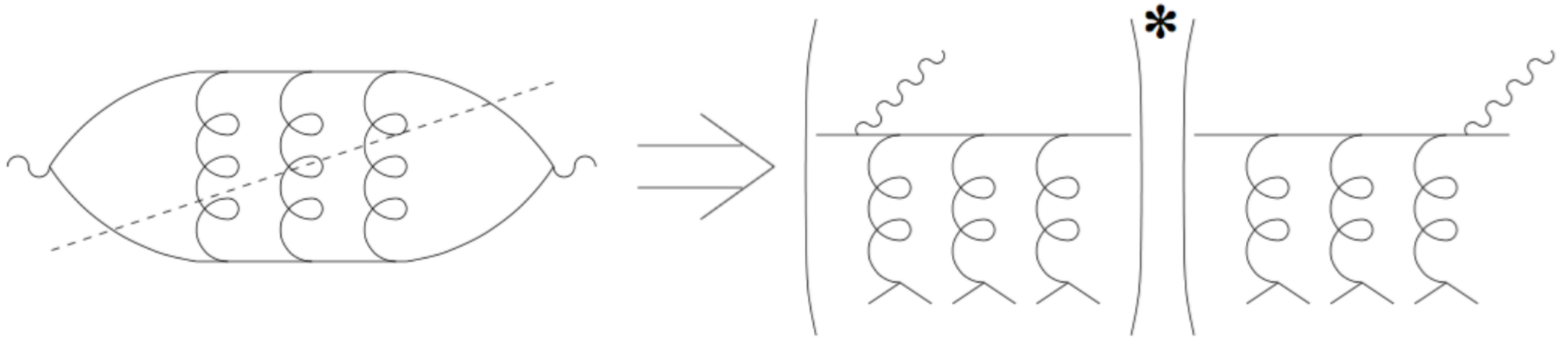
$$\mathrm{Im}\,\mathbf{W}_2^R(q) = \frac{N_c\tilde{\mathbf{e}}^2}{4\pi}q^2\left\langle\frac{\alpha_s}{\pi}A_4^2\right\rangle\left(\frac{4\pi^2}{T|\vec{q}|}\right)(n_+(1-n_+)-n_-(1-n_-))$$

$$\mathrm{Im}\,\mathbf{W}_4^R(q) = \frac{N_c\tilde{\mathbf{e}}^2}{4\pi}\left[-\frac{1}{6}\left\langle\frac{\alpha_s}{\pi}E^2\right\rangle+\frac{1}{3}\left\langle\frac{\alpha_s}{\pi}B^2\right\rangle\right]\left(\frac{4\pi^2}{T|\vec{q}|}\right)(n_+(1-n_+)-n_-(1-n_-))$$

$\left\langle\frac{\alpha_s}{\pi}A_4^2\right\rangle$ vanishes [Kaczmarek et al., arXiv:1301.7436]

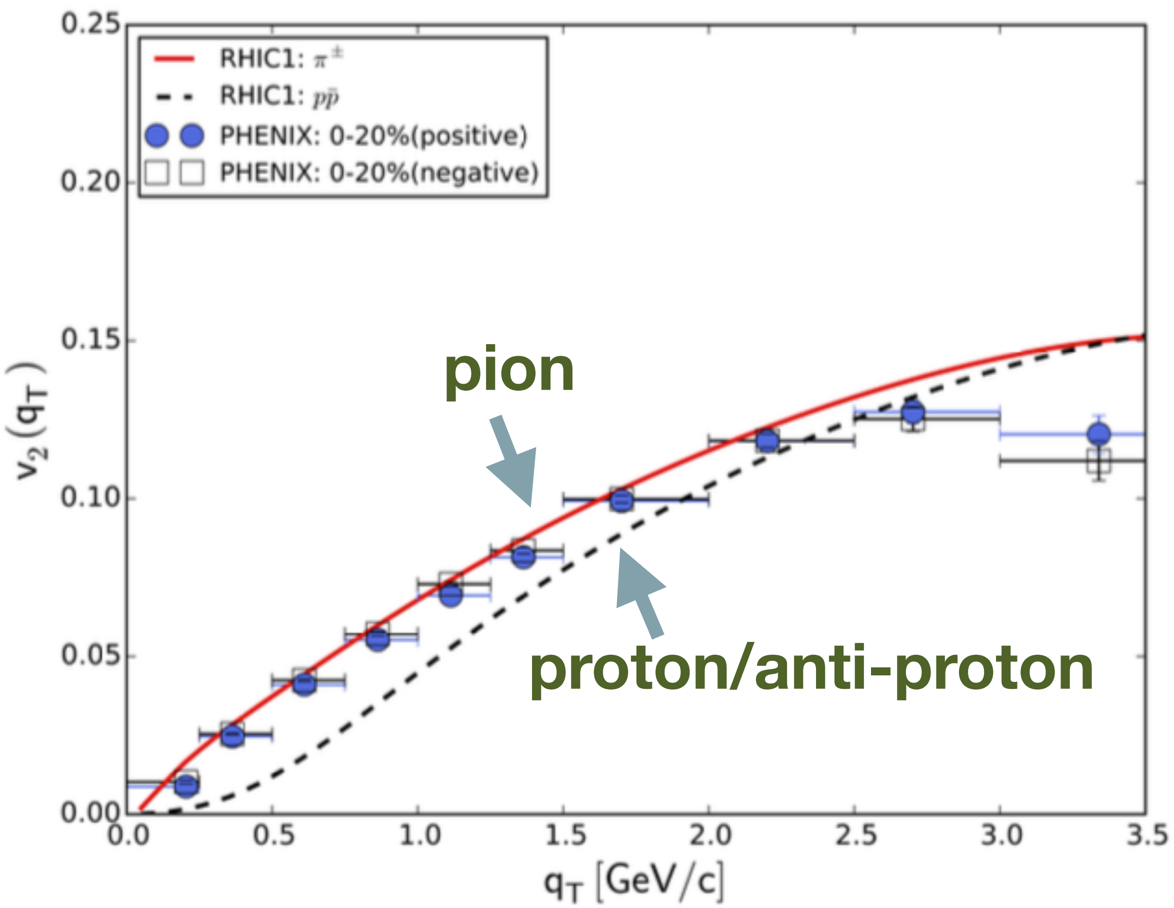
Direct Photon Production

- **Direct photons from hadronic gas**
  - use our results
- **Direct photons from sQGP**
  - our perturbative result vanishes at leading order
  - use **HTL (hot thermal loop)** by Arnold, Moore & Yaffe
    [JHEP 05, 051 (2003)]

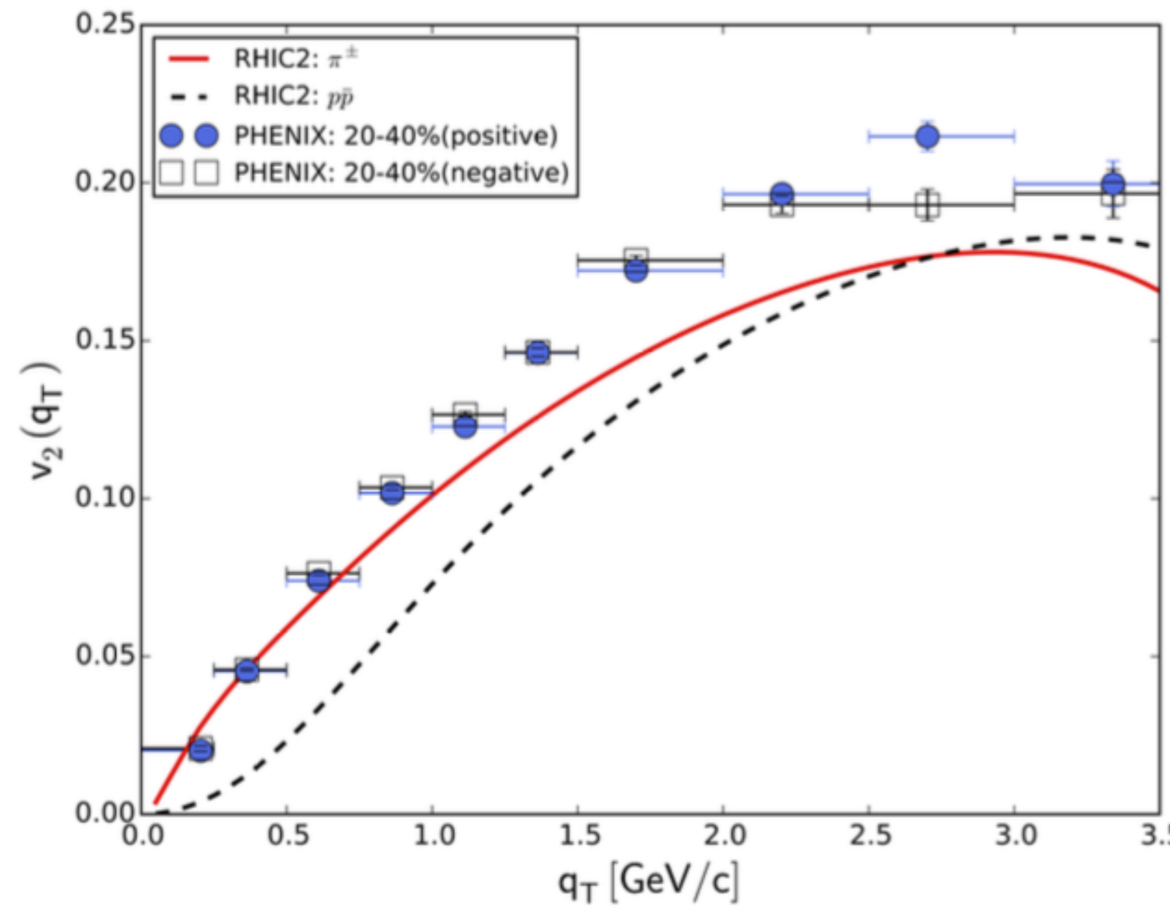


PHENIX charged particle elliptic flow

arXiv:1610.06213



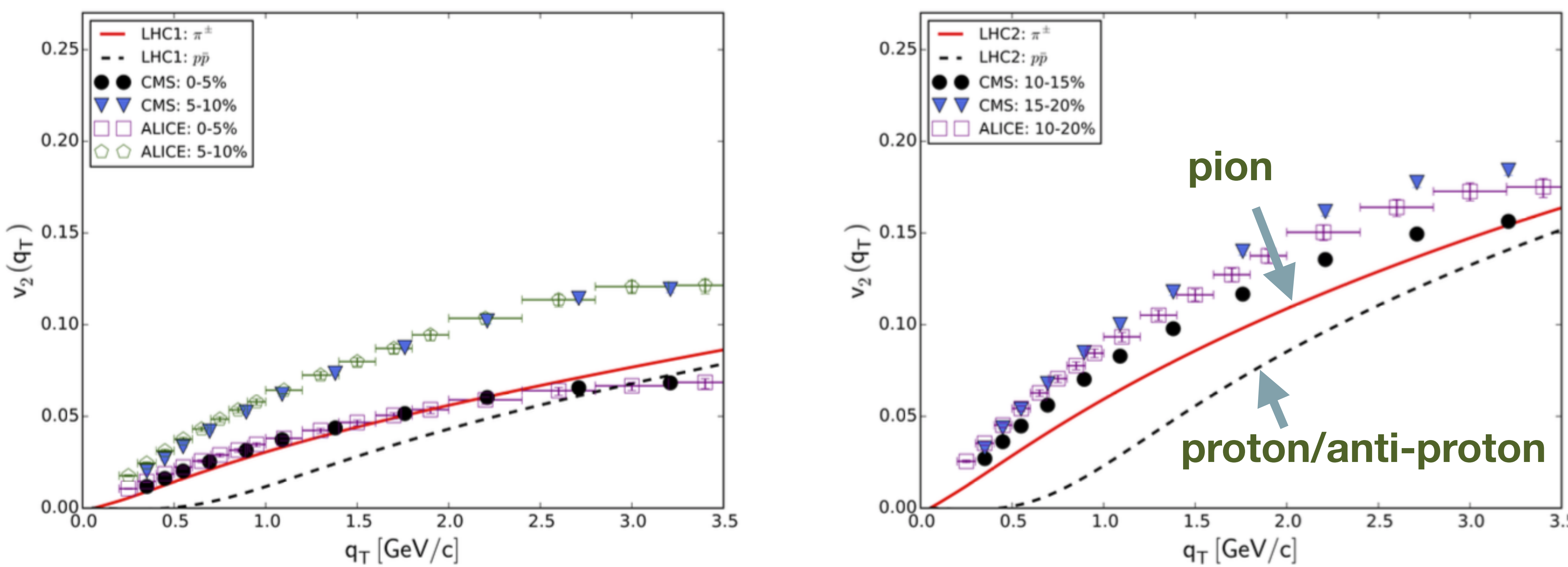
(a) 0-20% centrality



(b) 20-40% centrality

ALICE/CMS charged particle elliptic flow

arXiv:1610.06213

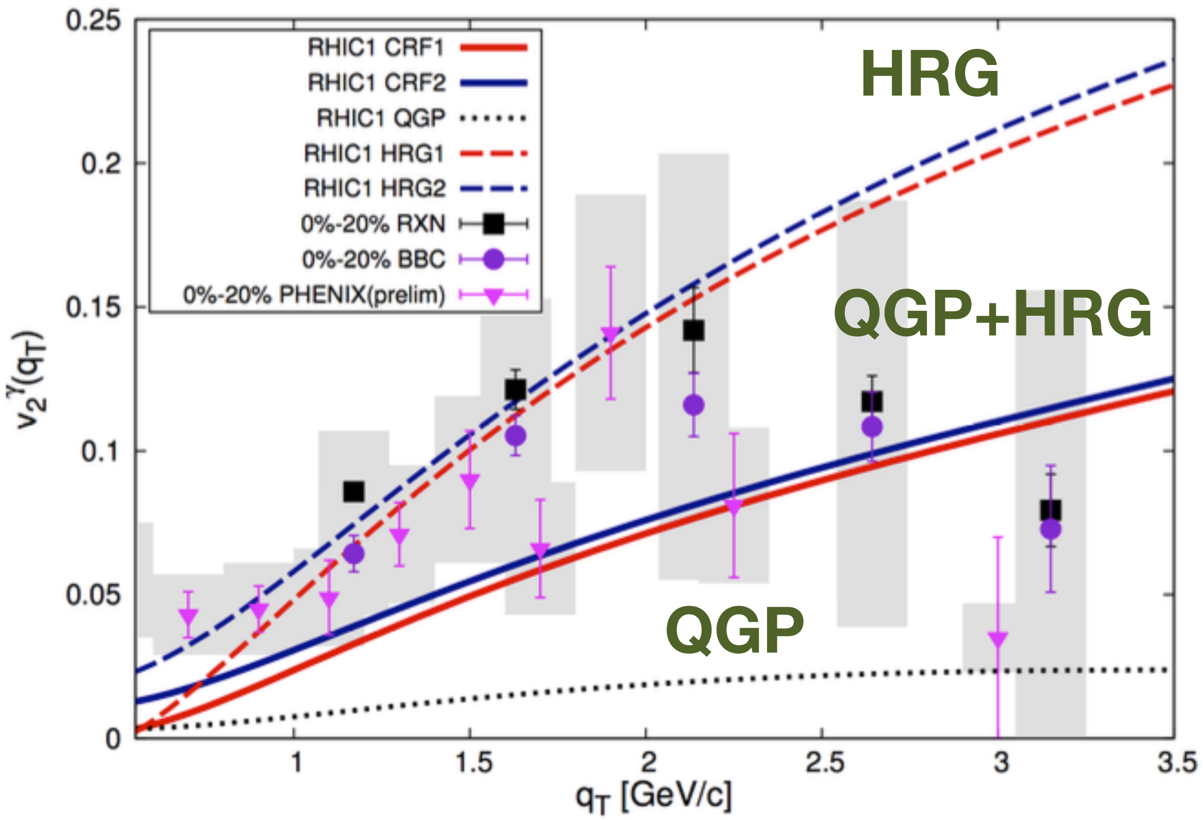


(a) 0-10% centrality

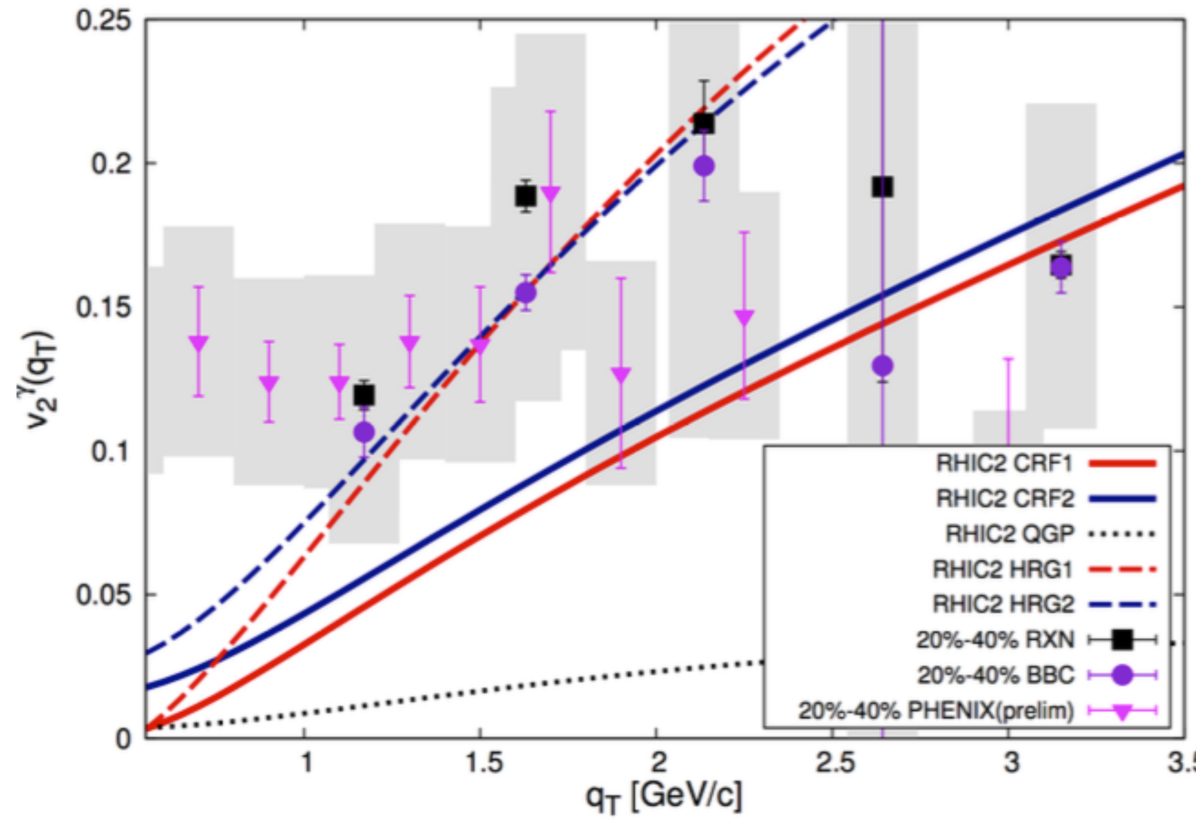
(b) 10-20% centrality

PHENIX direct photon elliptic flow

arXiv:1610.06213



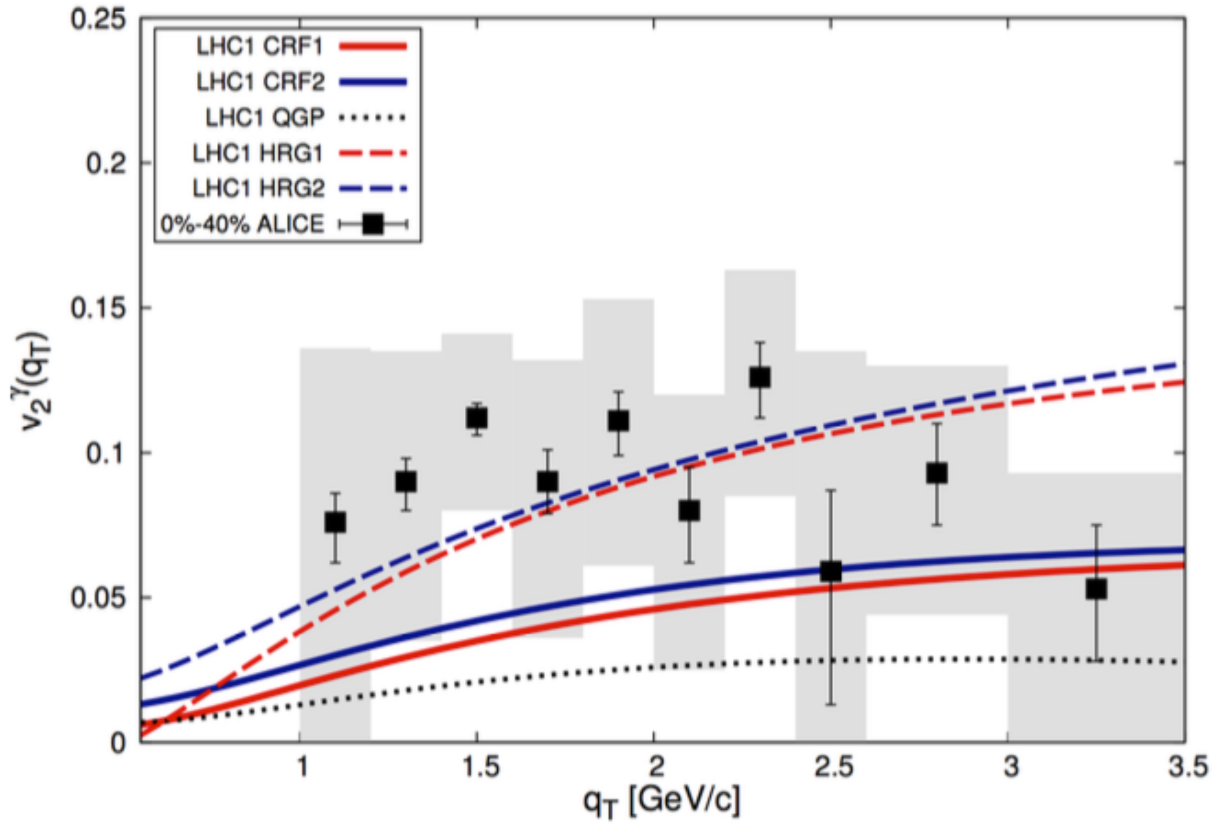
(a) 0-20% centrality



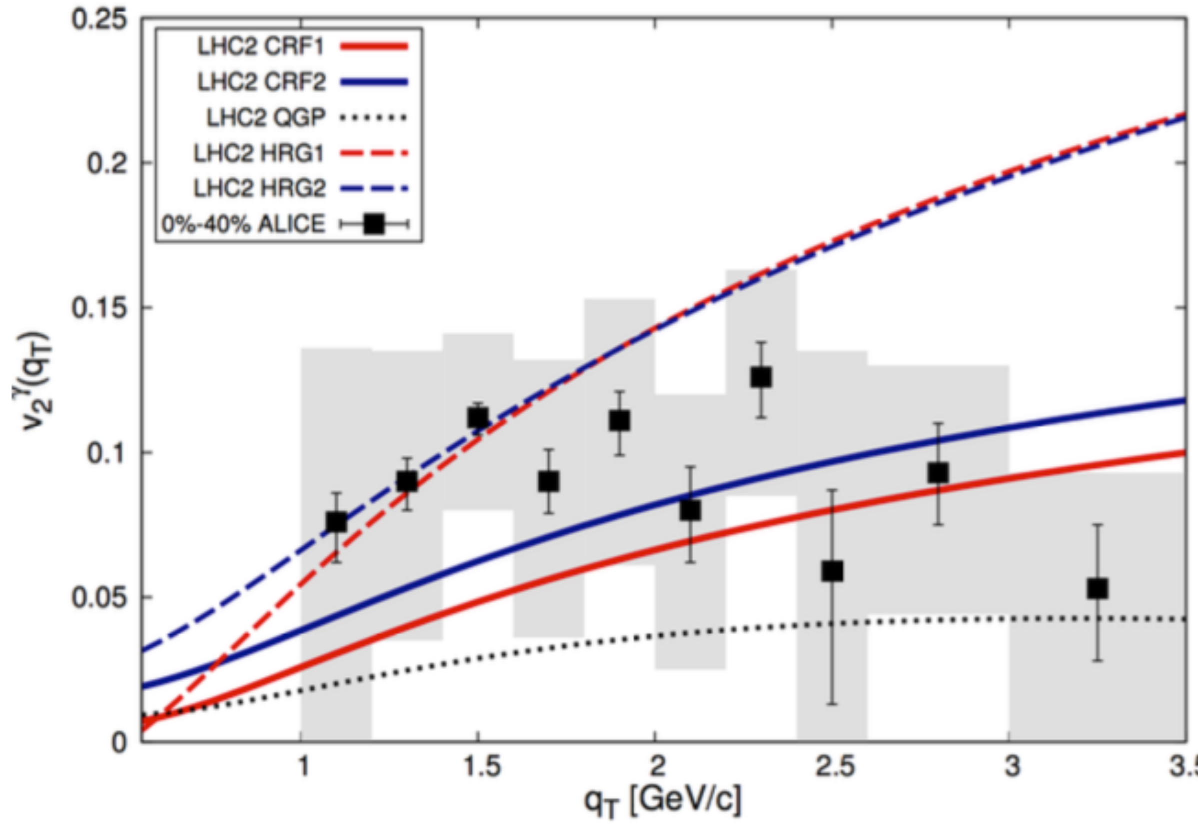
(b) 20-40% centrality

ALICE direct photon elliptic flow

arXiv:1610.06213



(a) 0-10% centrality



(b) 10-20% centrality

Conclusion

- **Low-mass dilepton enhancement**
  - partial restoration of chiral symmetry
  - mixing between vector & axial correlators
- **Charged particle elliptic flow**
  - pion is better than (anti-)proton
  - hadronic rates dominate the photon emissivity rates
  - still misses ALICE high qT data
- **Future Plan**
  - inclusion of nucleons for STAR BES

Many Thanks

with Good Memories

Pamyatnik V.I. Leninu
2016.10.30