Dilepton spectra as probes of the early stages of heavy-ion collisions

Maurice Coquet, 29th March, HP 2023, Aschaffenburg

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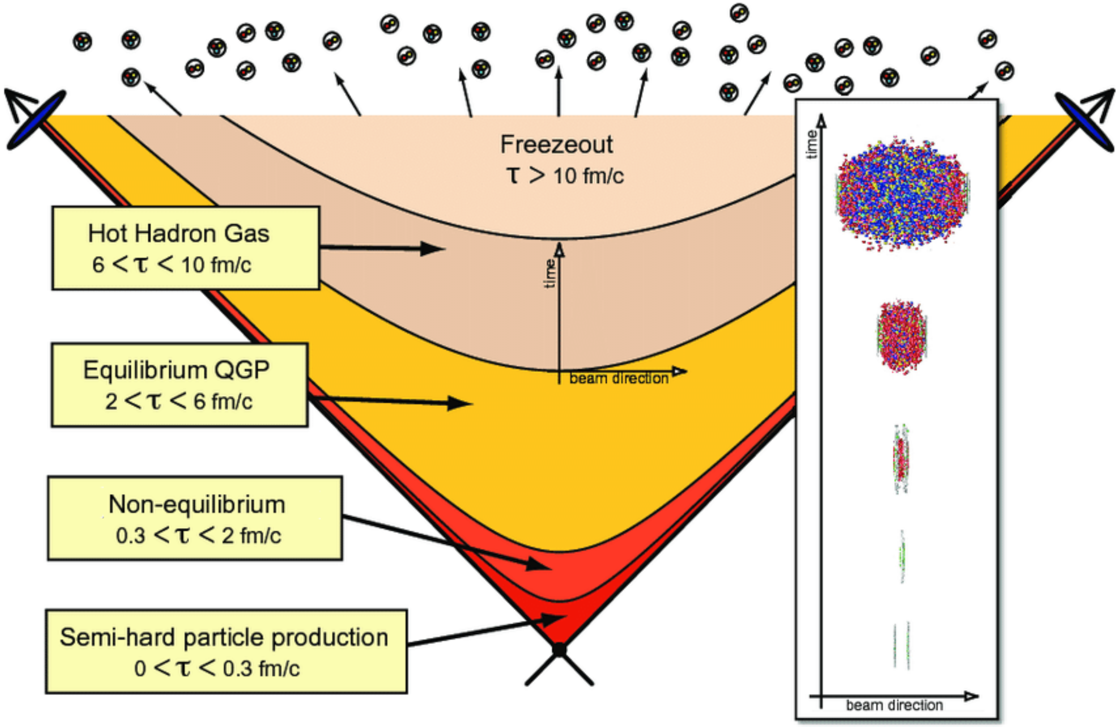
Nuclear Physics A 1030 (2023) 122579
Phys.Lett.B 821 (2021) 136626
+ work in progress

Space-time evolution of heavy-ion collisions

- A+A collisions: **different time scales** described by different effective theories
- Late stages very accurately modeled by hydrodynamic descriptions of expanding near-equilibrium QGP
- A challenge: matching between far-from-equilibrium initial state and hydrodynamics



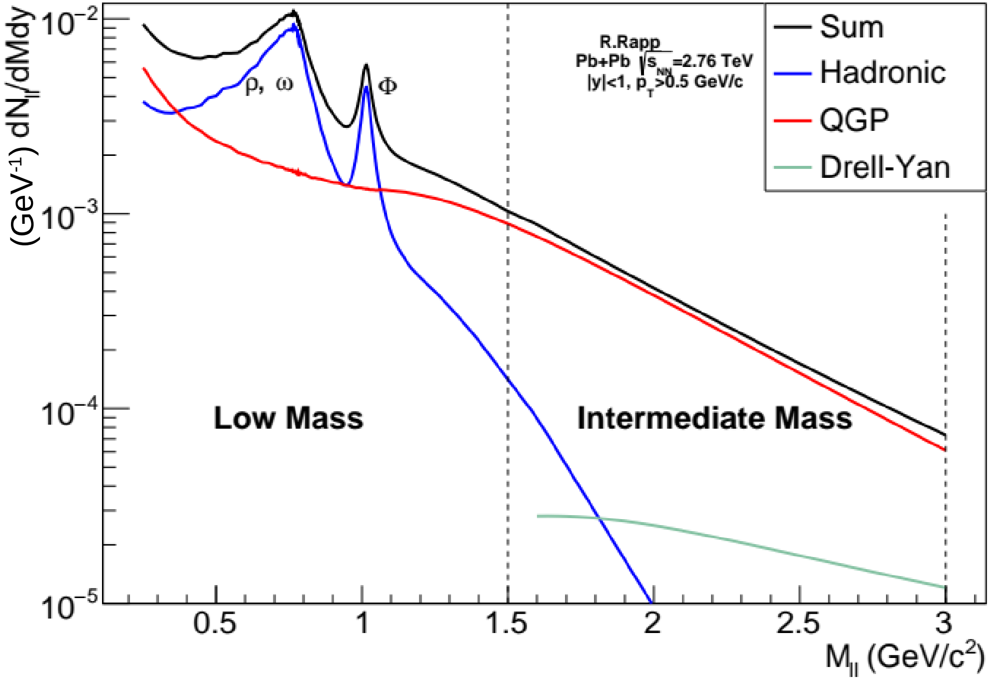
M.Strickland, Acta Physica Polonica B 45, 2355 (2014)

Dilepton production as a probe

- Electromagnetic interactions with the QGP have a small cross section

- Produced throughout the history of the collision → probe entire space-time dynamics

- Dilepton carry extra information: invariant mass → not affected by blue-shift



- Intermediate mass region (M > 1.5 GeV/c^2)
  →<u>Characterized by quarks and gluons degrees of freedom</u>

- High mass ↔ High T ↔ early times

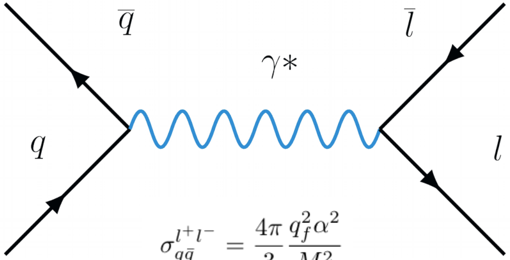
- Highly sensitive to early-times/pre-equilibrium emission

The ideal spectrum

- At LO, production by quark-antiquark annihilation:

$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3 2p_1} \frac{d^3p_2}{(2\pi)^3 2p_2} f_q(x,\mathbf{p}_1) f_{\bar{q}}(x,\mathbf{p}_2) |\mathcal{A}|^2 (2\pi)^4 \delta^{(4)}(P_1+P_2-K),$$

x: space-time coordinate of fluid cell
K: dilepton 4-momentum



$$\sigma_{q\bar{q}}^{l^+l^-} = \frac{4\pi}{3} \frac{q_f^2 \alpha^2}{M^2}$$

- Assume one dimensional Bjorken expansion:
→ boost invariant along the longitudinal direction
→ homogeneous in the transverse plane
→ Transverse flow neglected (high T ↔ early times)

- Considering ideal hydrodynamics, production rate **depends only on transverse mass $\mathbf{M_t}$**:

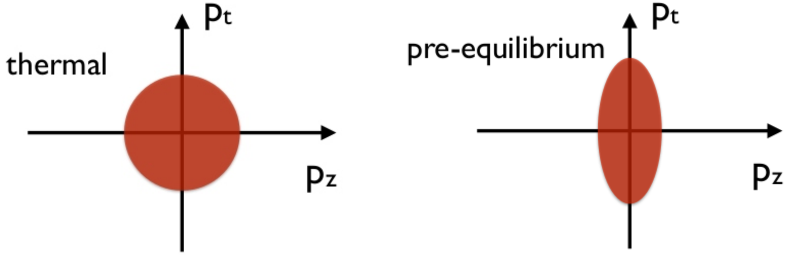
$$\left(\frac{dN^{l^+l^-}}{d^4K}\right)_{\text{ideal}} \propto \frac{1}{\boxed{M_t^6}} \frac{1}{A_\perp} (s\tau)^2_{\text{hydro}}$$
$$\propto \frac{1}{M_t^6} \left(\frac{dN_{\text{ch}}}{d\eta}\right)^{4/3}$$

L. D. McLerran and T. Toimela, Phys. Rev. D31(1985), 545

→ How pre-equilibrium effects manifest themselves in the spectra of dileptons ?

Features of pre-equilibrium: pressure asymmetry

- At early times, rapid longitudinal expansion → $P_L << P_T$



→ **momentum anisotropy** **breaks M_t scaling**, favoring small masses for a given M_t value

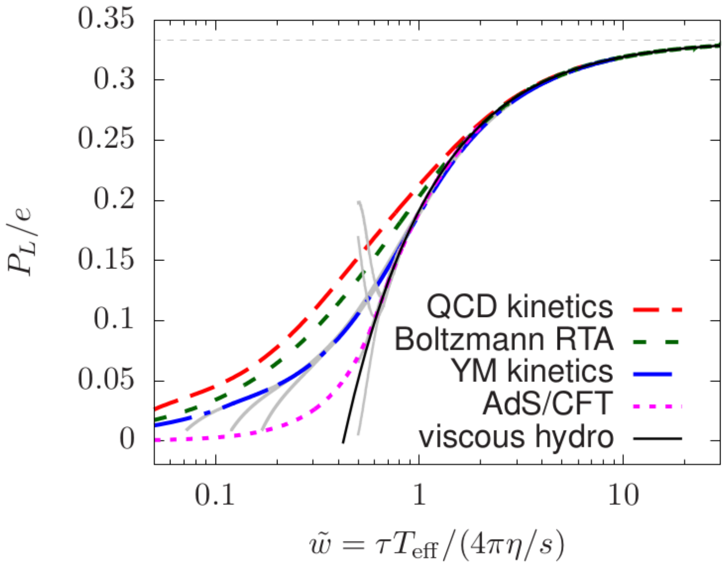
→ parametrize quark distribution with anisotropy variable **ξ**

$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD}\Big(-\sqrt{p_T^2 + \boxed{\xi^2(\tau)} p_L^2}/\Lambda(\tau)\Big)$$

- **Universality in pre-equilibrium** (attractor solutions)

  →Choose **QCD kinetics** to compute evolution of parameters

Phys. Rev. Lett. 123, 262301 (2019)



Features of pre-equilibrium: quark suppression

- Models predict a gluon-dominated medium at early times → transition towards a chemical equilibrium

  → quark suppression factor, defined as the ratio between quark and gluon energy density:

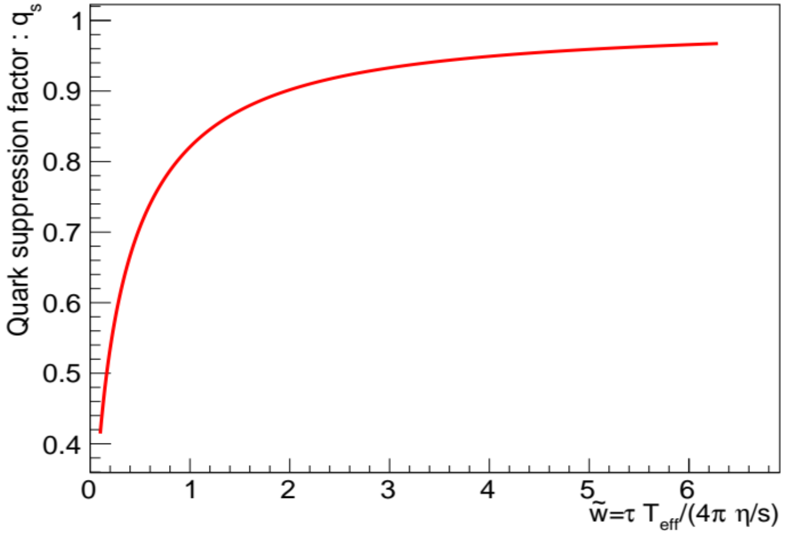
$$q_s(\tau) \propto \frac{e^{(q)}}{e^{(g)}}\Big(T(\tau)\Big)$$

  →Choose **QCD kinetics** to compute evolution of parameters

$$f_q(\tau, p_T, p_L) = \boxed{q_s(\tau)} f_{FD}\left(-\sqrt{p_T^2 + \xi^2(\tau) p_L^2}/\Lambda(\tau)\right)$$

- Quark suppression implies suppression of dilepton production, which is a global factor
  → **preserving M_t scaling**

X. Du, S. Schlichting: Phys. Rev. D 104, 054011 (2021)
Phys. Rev. Lett. 127, 122301 (2021)



Calculated with QCD kinetics

Results: mass spectra

- η/s <u>is not</u> the viscosity in the hydro regime, controls **time scale of applicability of hydro**

- larger η/s
  → later thermalization
  → lower initial temperature for fixed final entropy density

- Drell-Yan process calculated at NLO **dominates dilepton production at high mass**

- Very sensitive to quark suppression

→ access to early-stage chemistry
→ access to equilibration time (∝ η/s)

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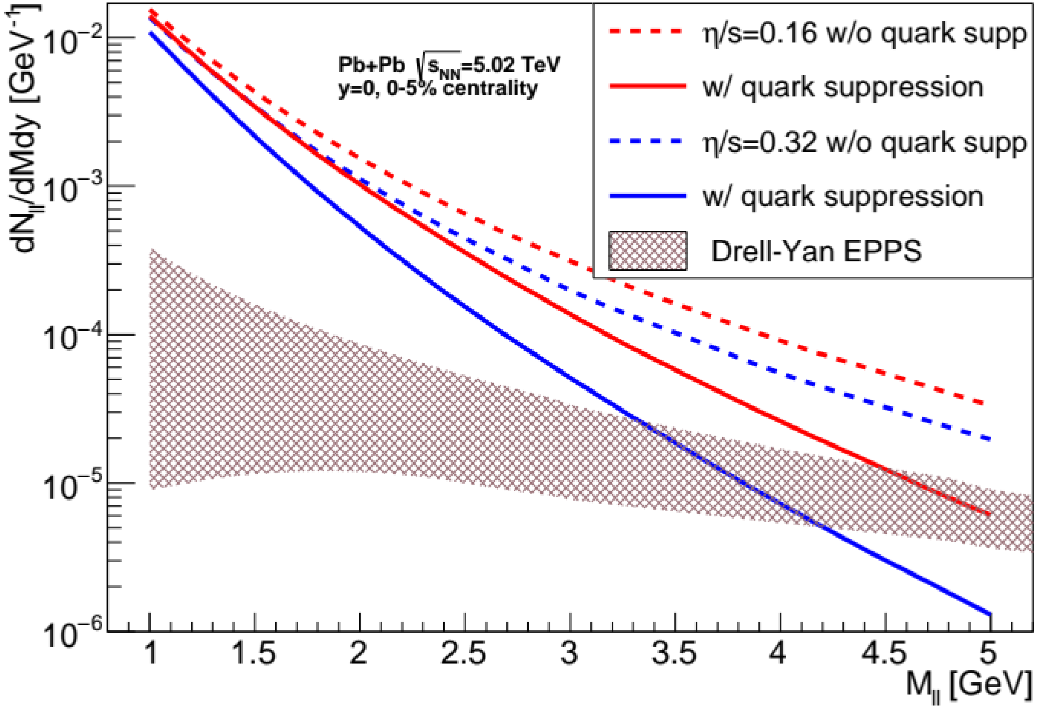

Results : M_t spectra

- Suppression of production yield due to **quark suppression**
- **Small breaking of M_t scaling** due to momentum anisotropy, favoring small masses for a given M_t value
- Spectra well fitted by the following formula:

$$\frac{dN^{l^+l^-}}{d^4K} \simeq \left(\frac{dN^{l^+l^-}}{d^4K}\right)_{\text{ideal}} \frac{\left(1+a\frac{\eta}{s}M_t^2/n\right)^{-n}}{\sqrt{1+b\frac{\eta}{s}M^2}}$$

- Inverse slope of the M_t spectrum → effective temperature:

$$T_{\text{eff}}(M_t) \equiv -\left[\frac{d}{dM_t}\ln\left(\frac{dN^{l^+l^-}}{d^4K}\right)\right]^{-1} \quad \rightarrow \quad T_{\text{eff}}(M_t) \simeq \frac{M_t}{6+2a\frac{\eta}{s}M_t^2}$$

- Drell-Yan enhanced for larger values of M at fixed M_t, **opposite behavior to QGP emission**.

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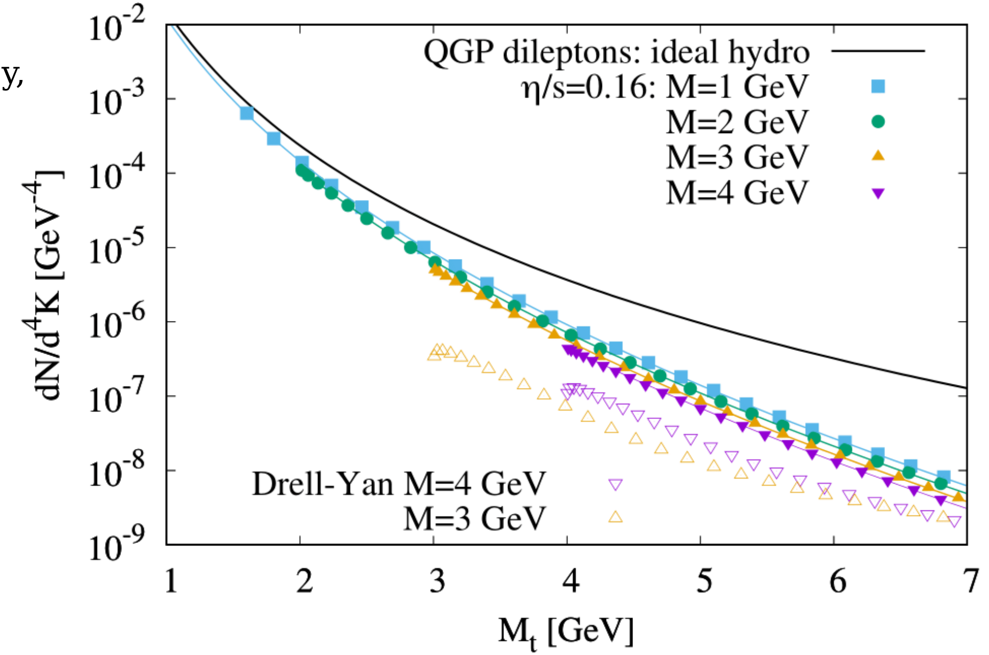
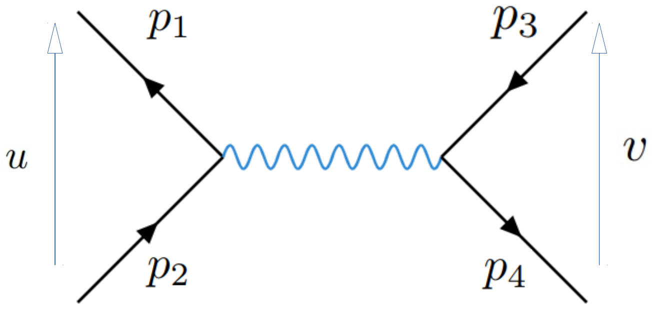


0-5 % centrality Pb-Pb 5.02 TeV, |y| < 1, η/s=0.16

Results: angular distribution of leptons

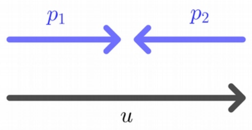


- Cross section (differential in leptonic momenta) favors alignment between incoming (u) and outgoing (v) relative 4-momenta:

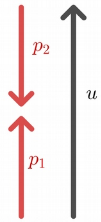
$$\frac{dN}{d^4x\,d^4K} \propto \frac{1}{M^4}\int_{p_1,p_2,p_3,p_4} f_1^q f_2^{\bar{q}}\,(2\pi)^4\delta^{(4)}(p_1+p_2-K)\,\delta^{(4)}\left(K-p_3-p_4\right) l_{\mu\nu}\Pi^{\mu\nu}$$

$$l_{\mu\nu}\Pi^{\mu\nu} \sim 4N_cM^4\left(1+\frac{(u\cdot v)^2}{M^4}\right)$$

- Outgoing leptons will tend to have same direction as incoming quarks
  → **expect opposite behaviors between DY and thermal dileptons**

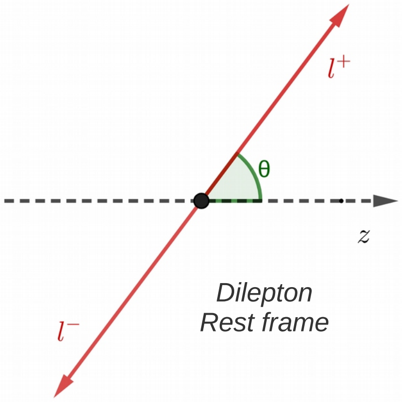


Drell-Yan

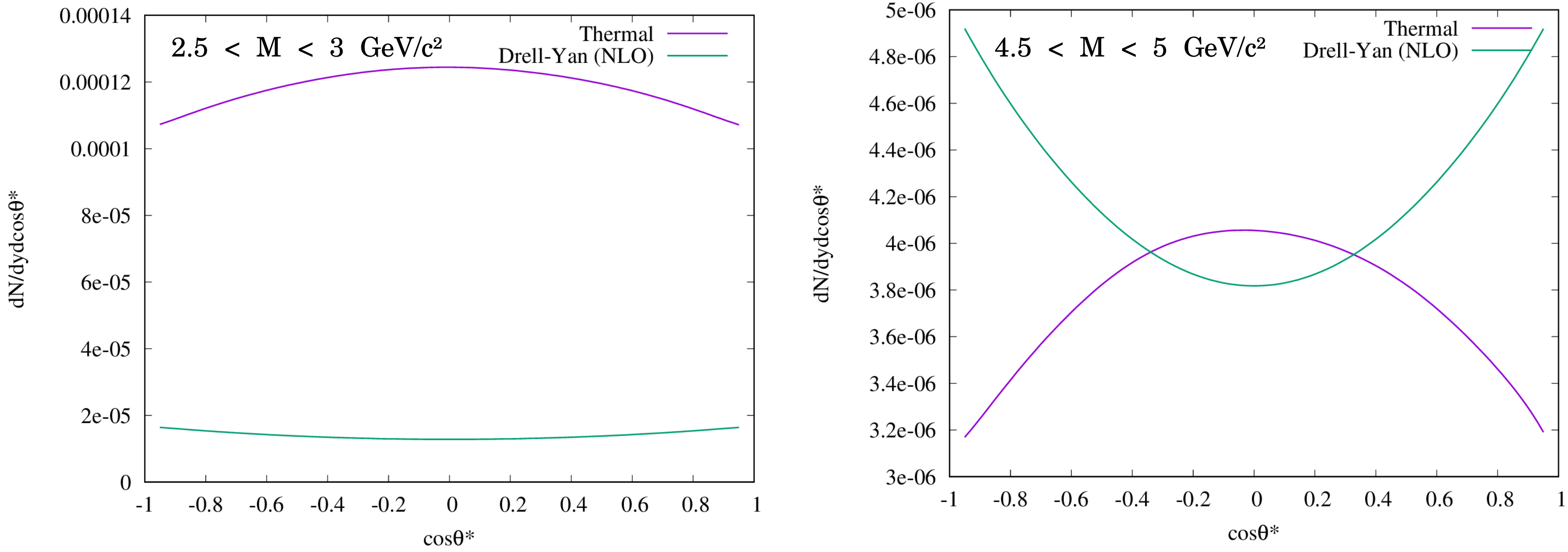


Pre-equilibrium

- Angle of positive lepton with respect to beam direction in dilepton rest frame:



Results: angular distribution of leptons


0-5 % centrality Pb-Pb 5.02 TeV, |y| < 1, η/s=0.16

- cosθ* distribution for "thermal" dileptons peaks at zero while DY peaks at ± 1
  → possible handle to disentangle two contributions
- Thermal part sensitive to anisotropy:
  → for $2.5 < M < 3$ GeV/c²: ~16% effect, for $4.5 < M < 5$ GeV/c²: ~30%

→ Direct measure of plasma anisotropy as a function of time

Conclusion

- Dilepton spectrum sensitive to early-time dynamics
- Gives **access to η/s** that controls the **equilibration time** (→ can be inferred by measuring the slope), as well as **early-stage chemistry**
- Different behavior of QGP production and Drell-Yan production as a function of **M at fixed M_t**
- Angular distribution of single lepton gives access to **plasma anisotropy** as a function of time

Thank you !

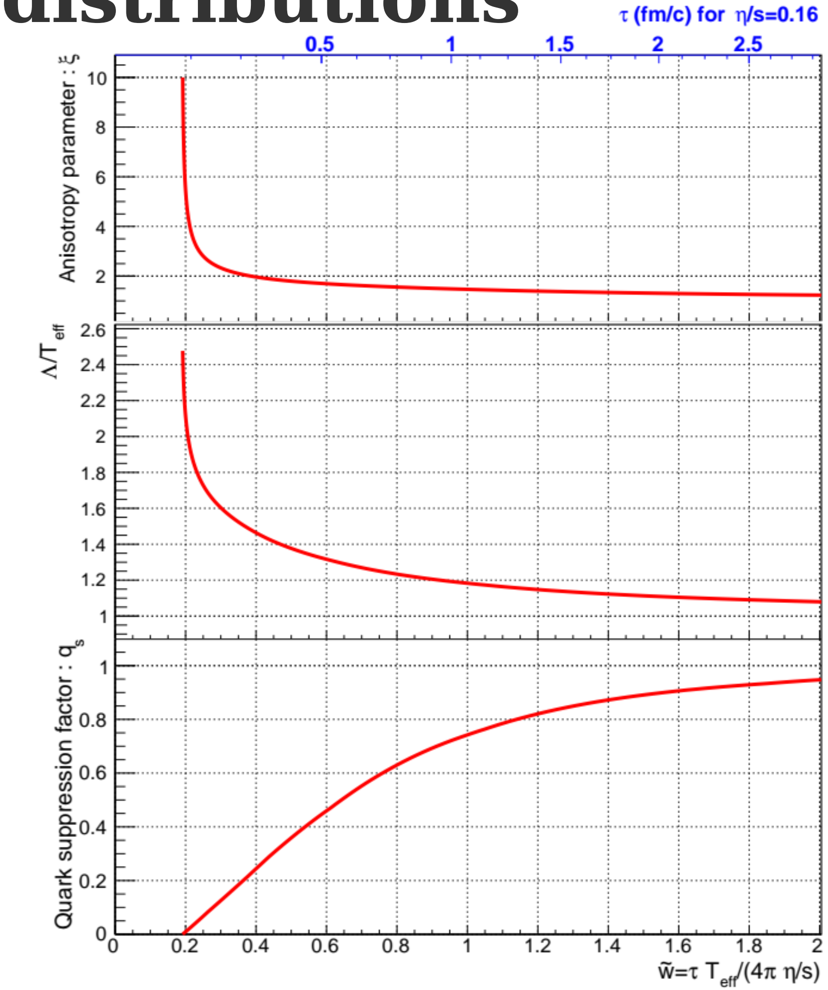
Backup

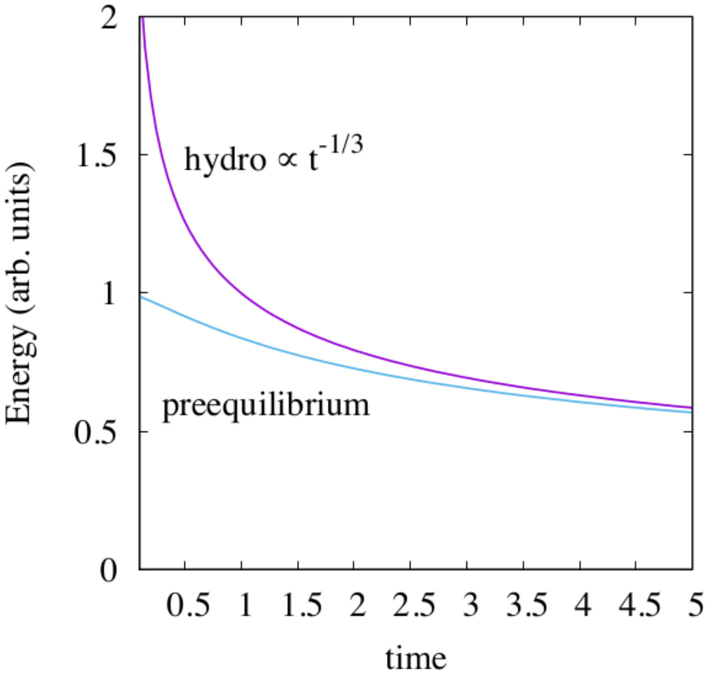
Out-of-equilibrium quark distributions

Distribution for quarks anisotropic in momentum space :

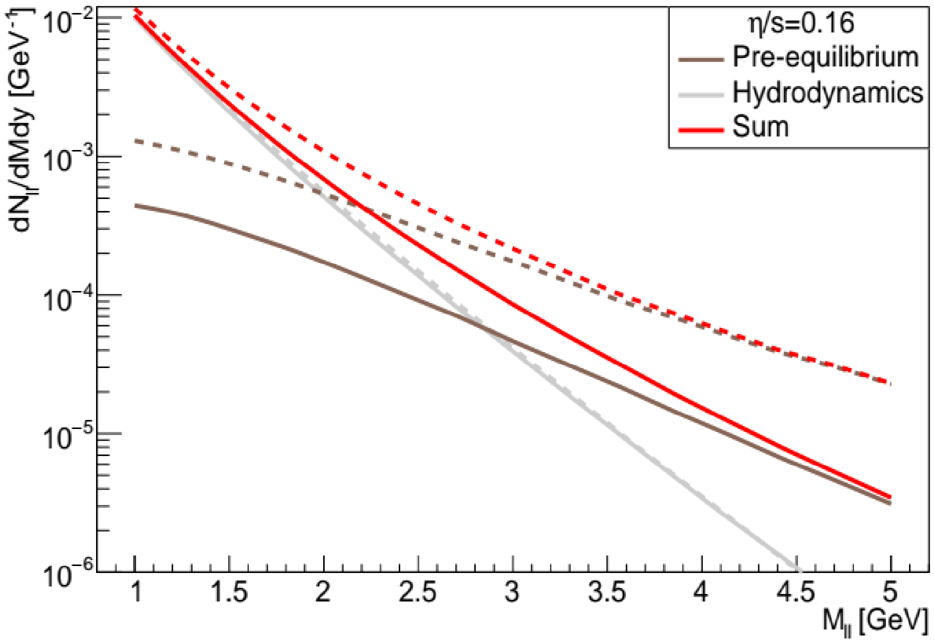
$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD}\Big(-\sqrt{p_T^2 + \xi^2(\tau) p_L^2} / \Lambda(\tau) \Big)$$

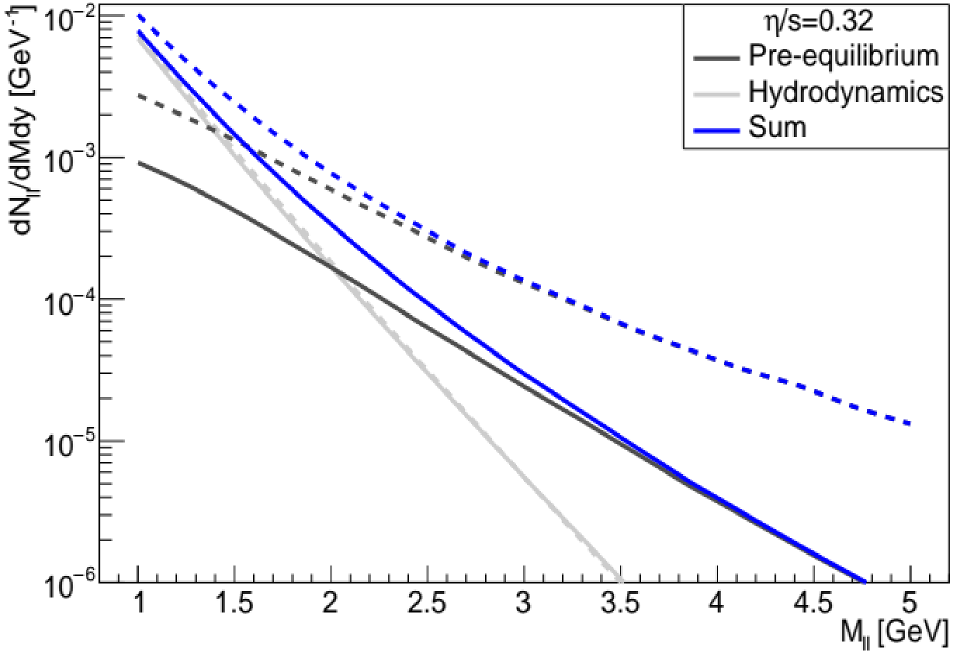
→ Depend on Λ (anisotropic effective temperature), anisotropy parameter ξ calculated w/ P_L/e, and quark suppression factor q_s





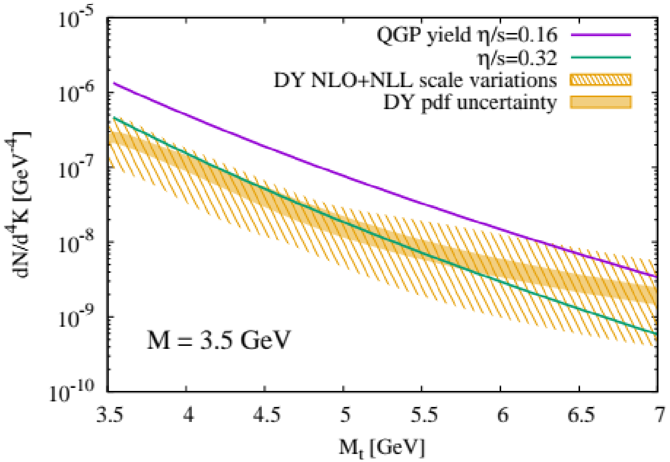
Results: time decomposition



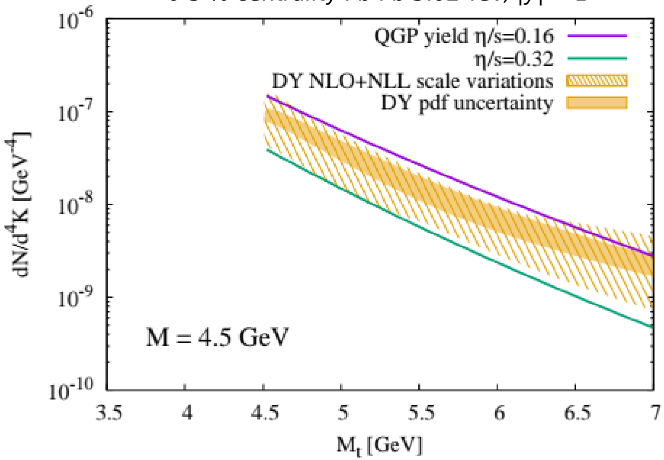


- Since η/s controls time scale for applicability of hydrodynamics; depending on value of η/s considerable contributions from pre-equilibrium regime (w<1)
- → larger viscosity → later thermalization → more contribution from pre-equilibrium

Backgrounds & scalings



0-5 % centrality Pb-Pb 5.02 TeV, |y| < 1



- Main backgrounds in intermediate mass region :
→ semileptonic decays of heavy flavours (rejectable based on displacement from primary vertex)
→ Drell-Yan production in the initial state.
- Drell-Yan contribution calculated using DYTurbo software, evaluated at NLO with resummed NLL (+Sudakov form factor includes non-perturbative contribution)

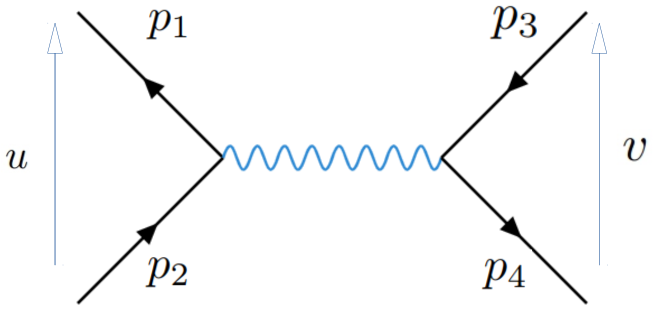
<u>Scaling properties</u>

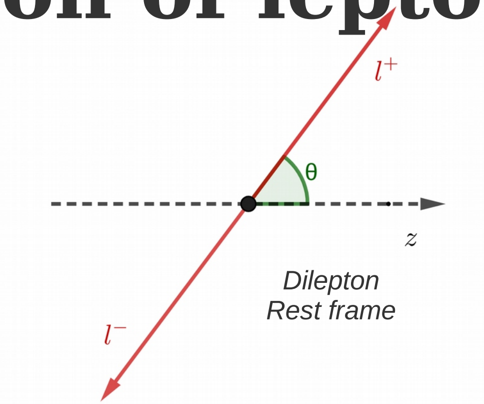
- <u>System size/centrality:</u> Ideal spectrum scales with system size like $(dN_{ch}/d\eta)^{4/3}$
  → scales like space-time volume

  → pre-equilibrium effects (a & b parameters) scale like $(dN_{ch}/d\eta)^{-1/3}$ (up to event by event fluct.)
- <u>Collision energy:</u> Ideal spectrum scales with $\sqrt{s_{NN}}$ like $(dN_{ch}/d\eta)^2$

  → pre-equilibrium effects scale like $(dN_{ch}/d\eta)^{-1}$

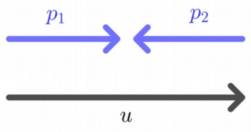
Results: angular distribution of leptons



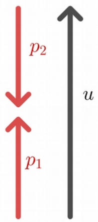


$$\frac{dN}{d^4x\,d^4Q} \propto \frac{1}{Q^4}\int_{p_1,p_2,p_3,p_4} f_1^q f_2^{\bar{q}}\;(2\pi)^4\delta^{(4)}(p_1+p_2-Q)\delta^{(4)}\left(Q-p_3-p_4\right) l_{\mu\nu}\Pi^{\mu\nu}$$

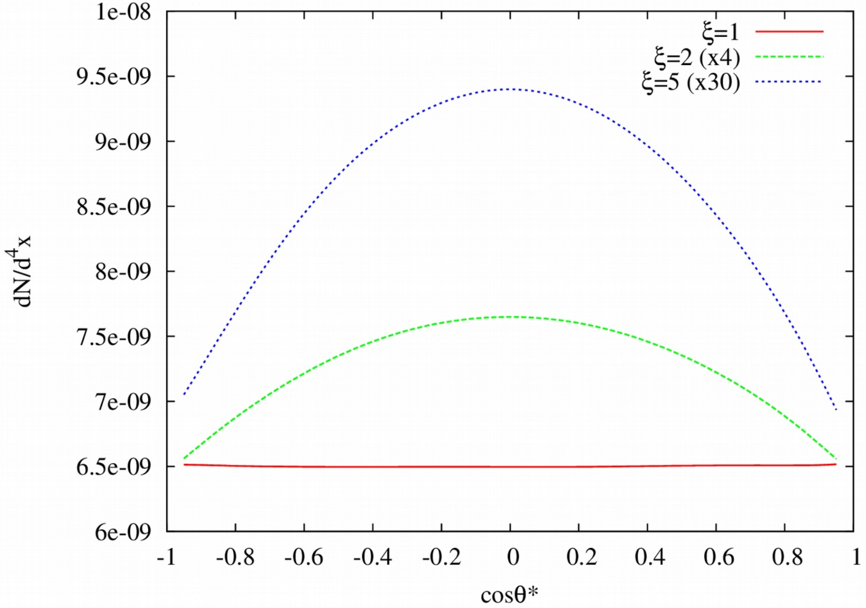
$$l_{\mu\nu}\Pi^{\mu\nu} \sim 4N_c Q^4\left(1+\frac{(u\cdot v)^2}{Q^4}\right)$$



Drell-Yan



Pre-equilibrium

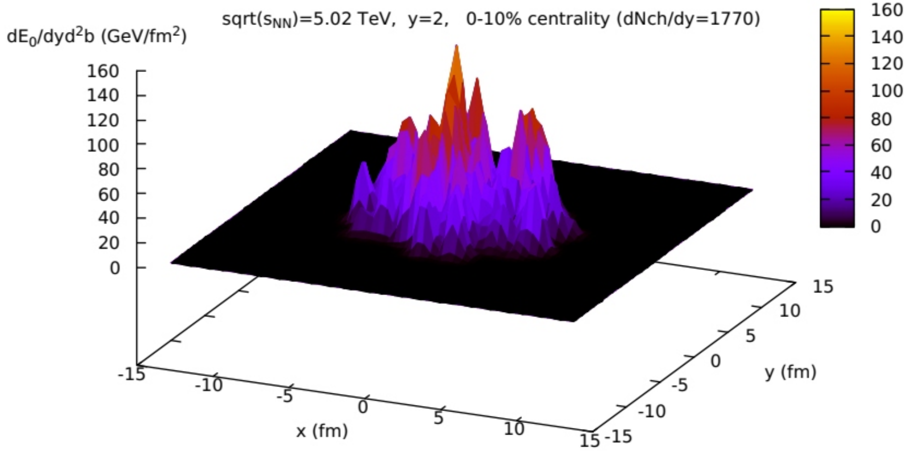


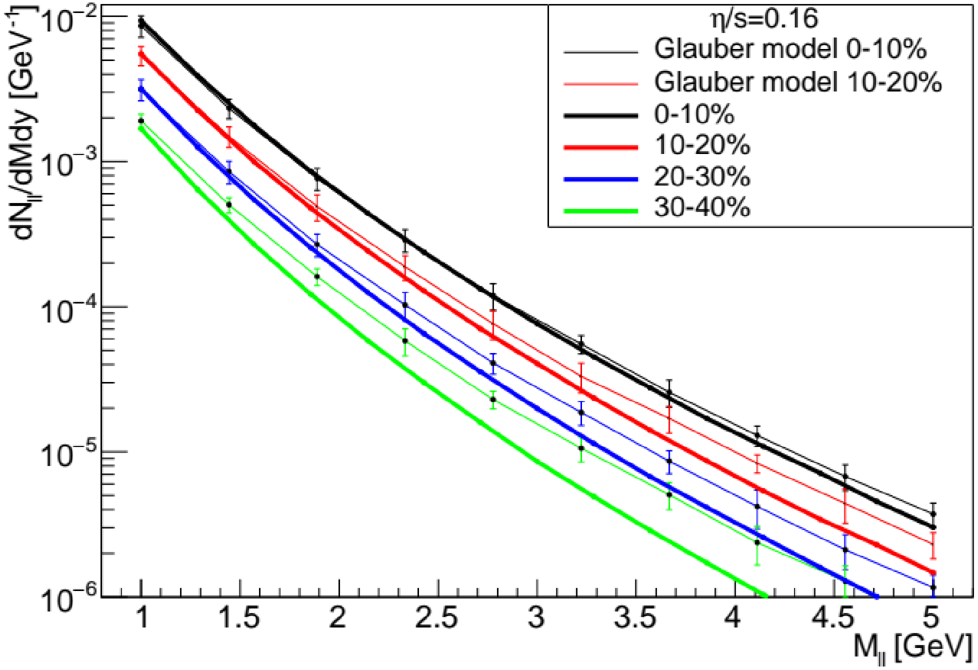
Estimating the transverse fluctuations

- Modelling of event-by-event fluctuations (hot spots) using a TMD-Glauber model : parametrization of gluon distributions in nucleons + Glauber→ parameters tuned to reproduce ALICE data for $dN_{ch}/d\eta$

$$\frac{dN_g}{d^2\mathbf{b}\,d^2\mathbf{P}\,dy} = \frac{\alpha_s N_c}{\pi^4 \mathbf{P}^2 (N_c^2-1)} \int \frac{d^2\mathbf{k}}{(2\pi)^2}\, \Phi_A(x,\mathbf{b}+\mathbf{b}_0/2,\mathbf{k})\ \Phi_B(x,\mathbf{b}-\mathbf{b}_0/2,\mathbf{P}-\mathbf{k})$$

- Important for large invariant mass region in more peripheral events

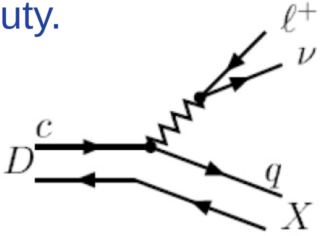


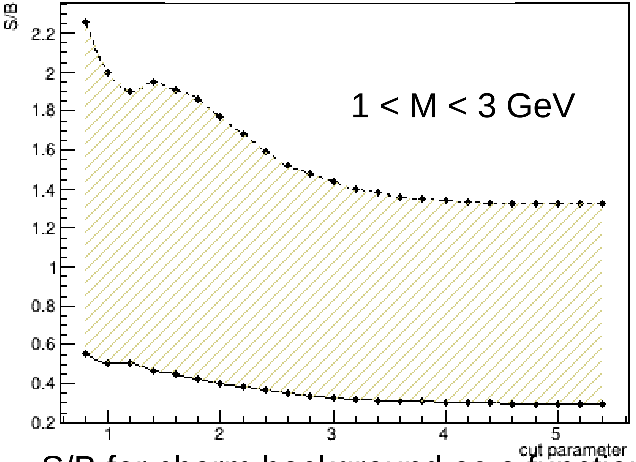


T. Lappi and S. Schlichting, Phys. Rev. D 97 (2018) no.3, 034034
S. Schlichting, X. Du, private communication

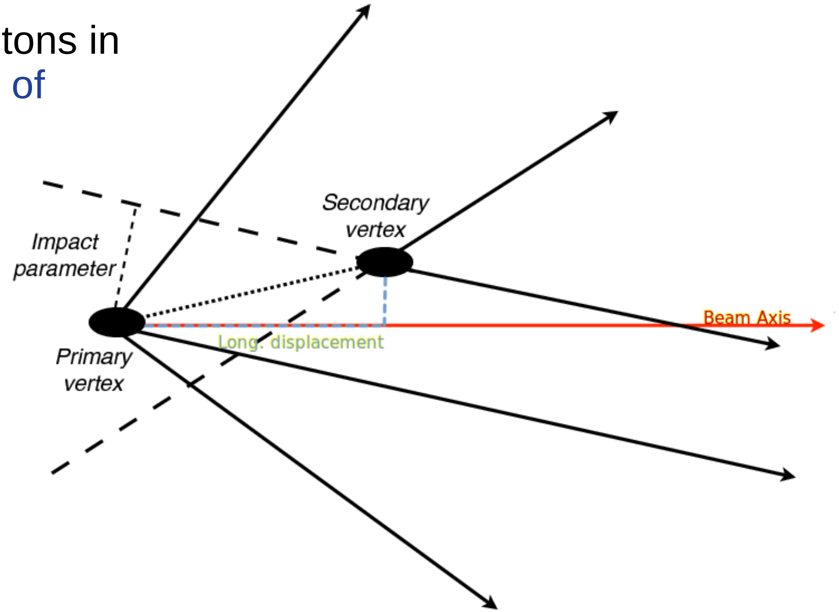
Background suppression with LHCb

→ Dominant background for intermediate mass dileptons in heavy ion collisions at 5.02 TeV : semileptonic decay of charm and beauty.





S/B for charm background as a function of IP cut, with $0.5 < R_{AA} < 1$ for D and Λ_c



Rejection of background:
→ impact parameter of the single-track muons
→ longitudinal displacement of the secondary vertex

- LHCb upgrade 2 setup for heavy ion collisions would provide appropriate secondary vertexing