The iEBE package

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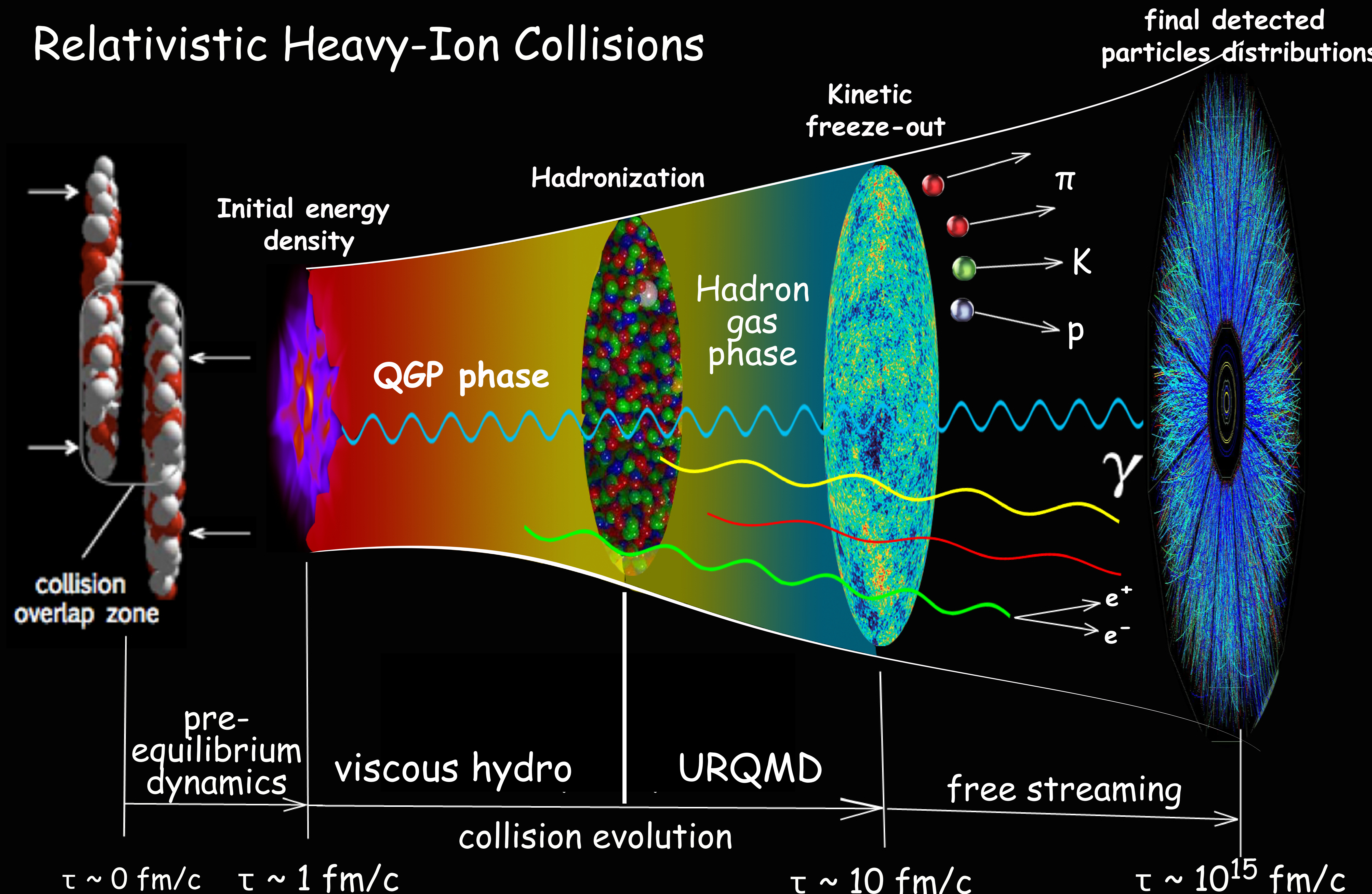
In collaboration with Zhi Qiu, Jia Liu, Chris Plumberg, Jean-Francios Paquet, Jonah Bernhard, Ulrich Heinz, Steffen Bass, and Charles Gale

June 17, 2014 JET Collaboration Meeting

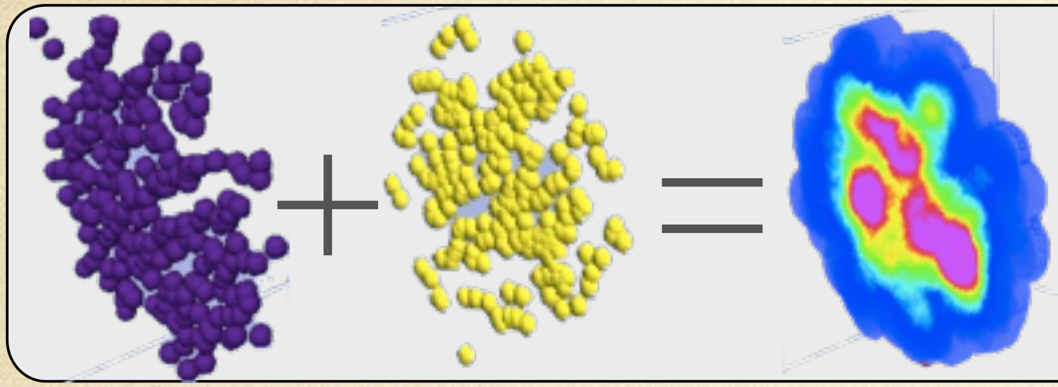
Little Bang


Relativistic Heavy-Ion Collisions
final detected
particles distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
π
K
p
Hadron
gas
phase
QGP phase
γ
e+
e-
collision
overlap zone
pre-
equilibrium
dynamics
viscous hydro
URQMD
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

IEBE simulation work flow

OSU-Duke

Initial Condition

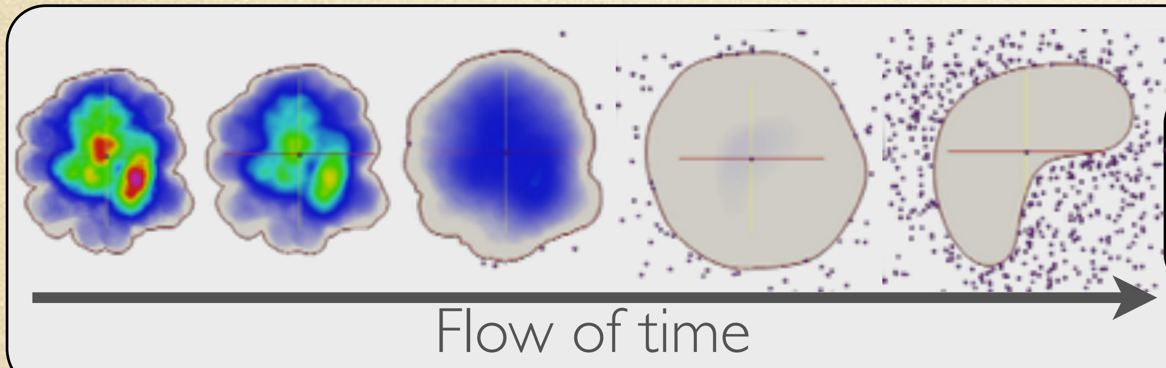


Generate Initial Conditions

superMC (C++)

https://github.com/chunshen1987/iEBE.git

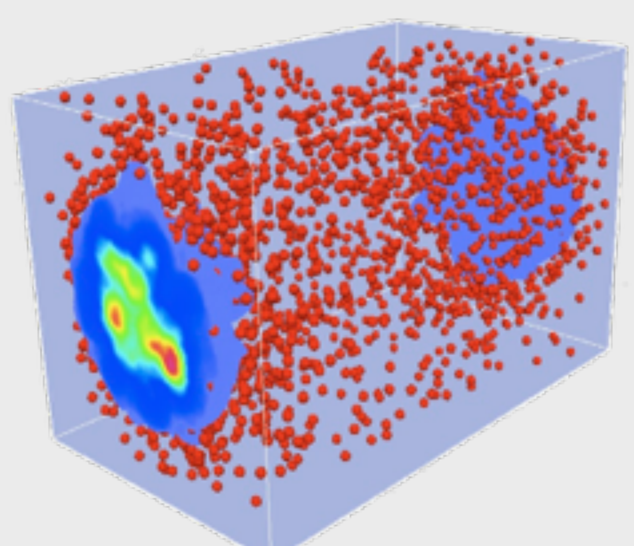
Hydrodynamics



Hydrodynamic simulations

VISHNew (FORTRAN)

Cascade



Particle emission

Hadron re-scattering

Collect particle information into observables

iSS (C++)

UrQMD (FORTRAN)

binUtilities (Python)

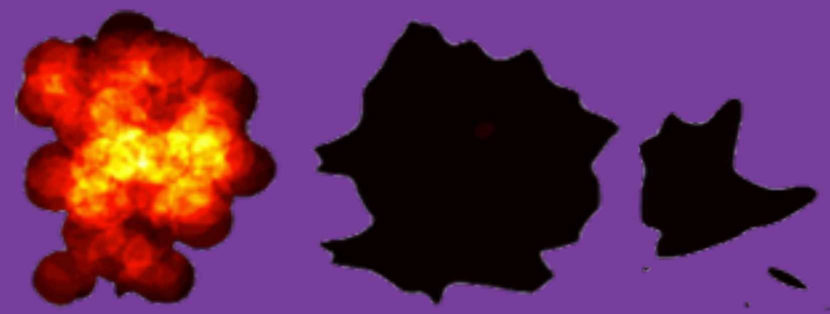
State-of-the-art hydrodynamic modeling

OSU-Duke

https://github.com/chunshen1987/iEBE.git

Initial Condition Generators (MC-KLN, MC-Glauber)

Hydrodynamic Simulations (VISH2+1)



UrQMD

Hadrons spectra & v_n

e-b-e VISHNU

HydroInfo Package

$u^\mu, \pi^{\mu\nu}$

Thermal Photon Emission Rates

Thermal Photon Interface

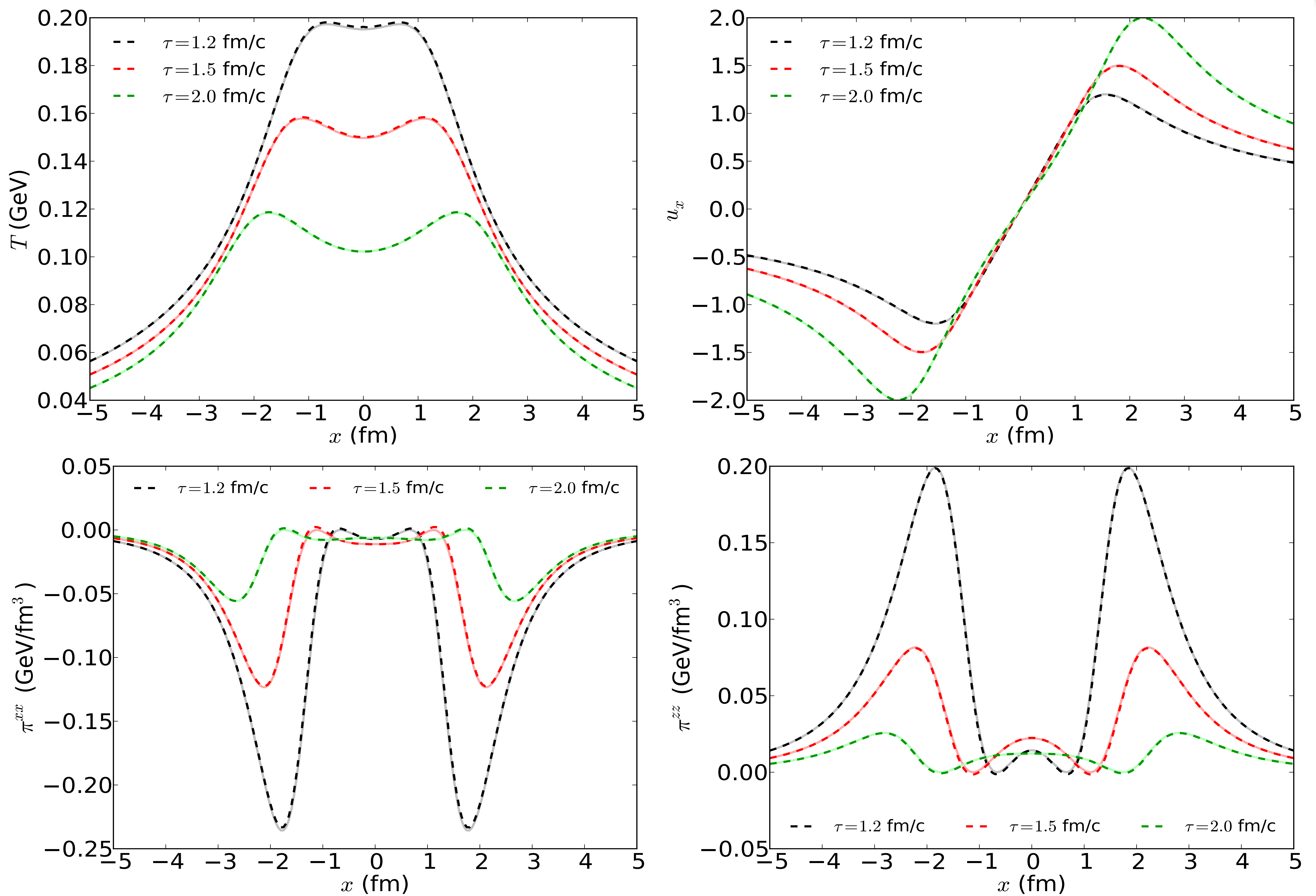
https://github.com/chunshen1987/iEBE.git

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} q_\mu q_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

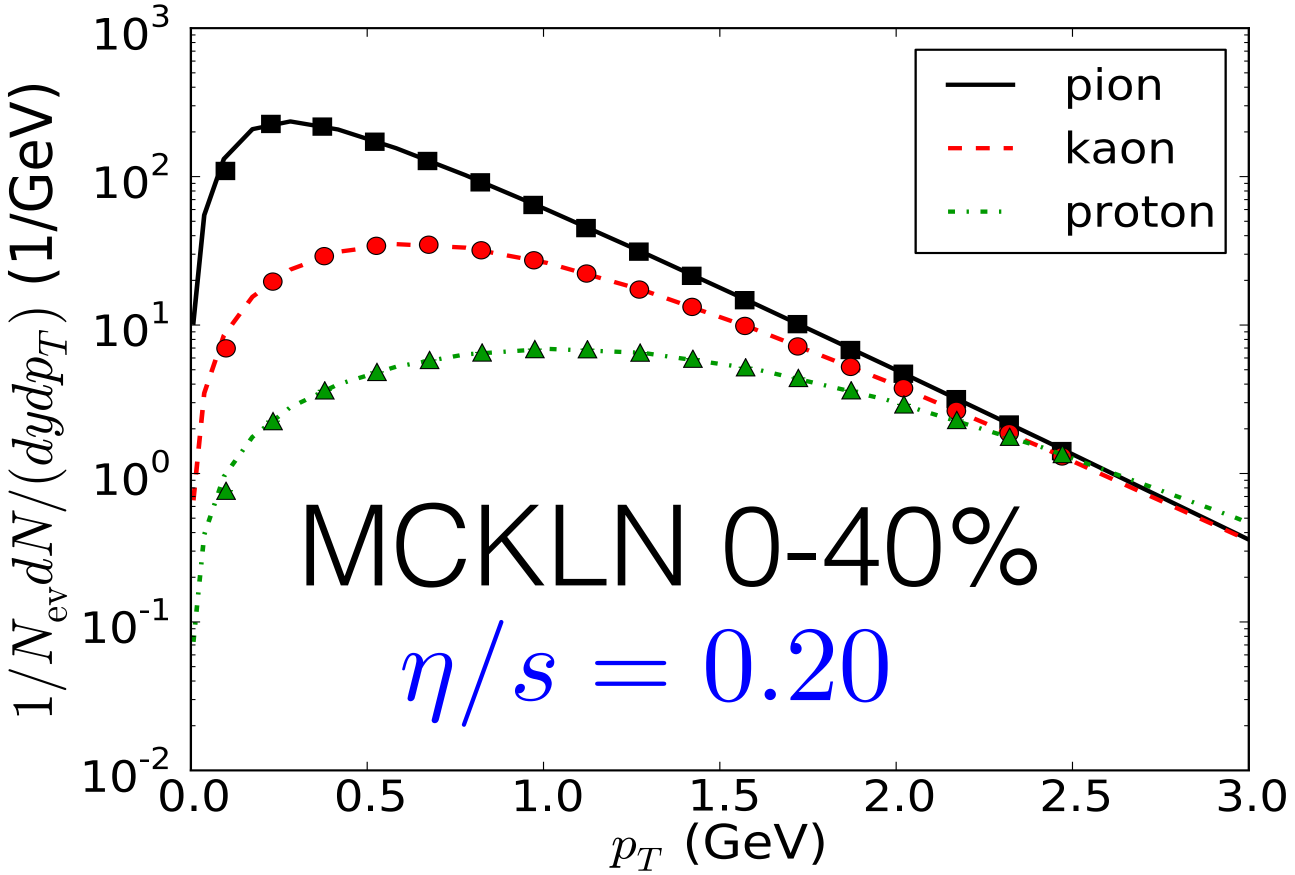
$$E\frac{dN^\gamma}{d^3p} = \int d^4x\, q\frac{dR}{d^3q}$$

Photon spectrum & v_n

Code test VISH2+1 with Gubser's flow



Code test iSS particle sampler



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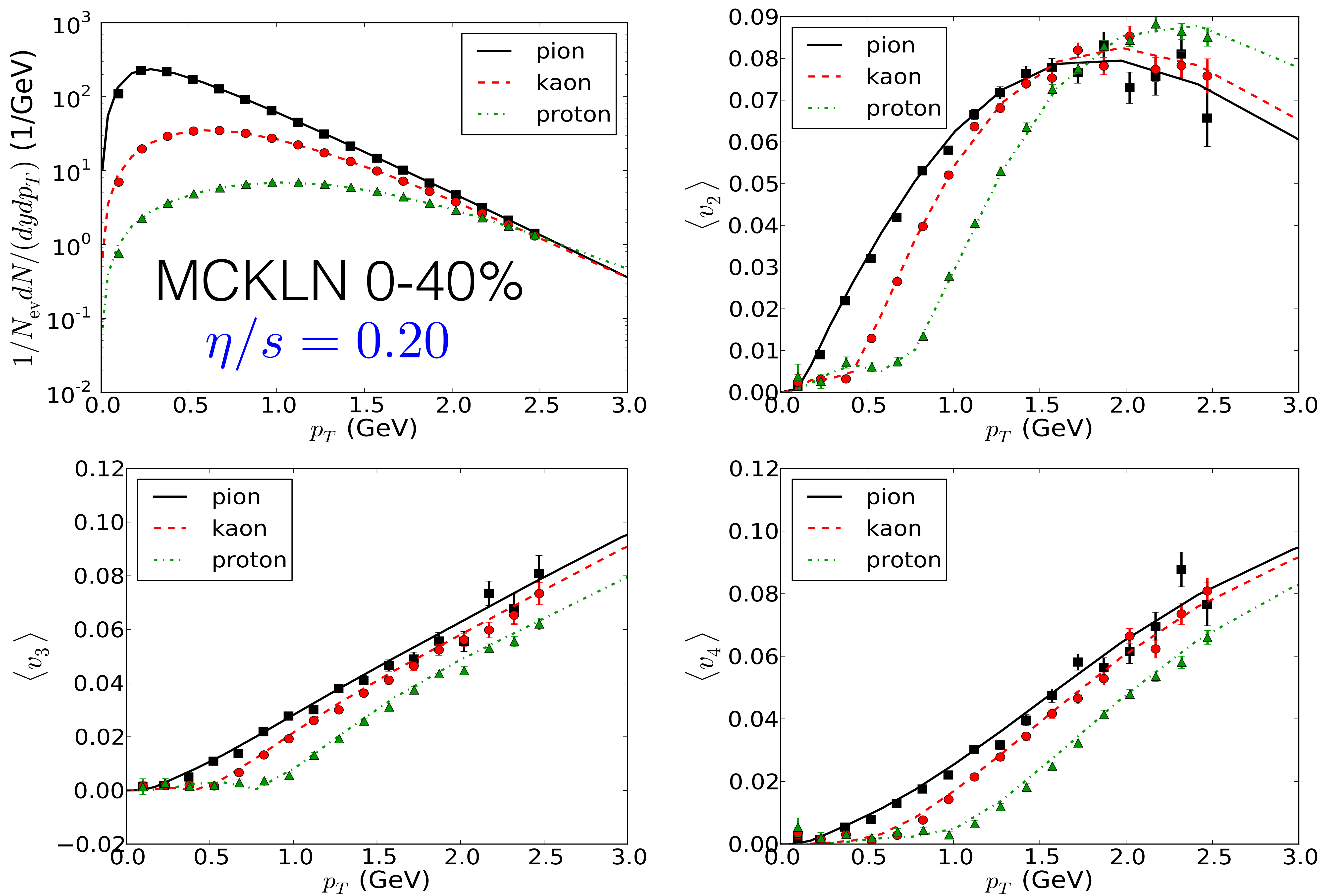

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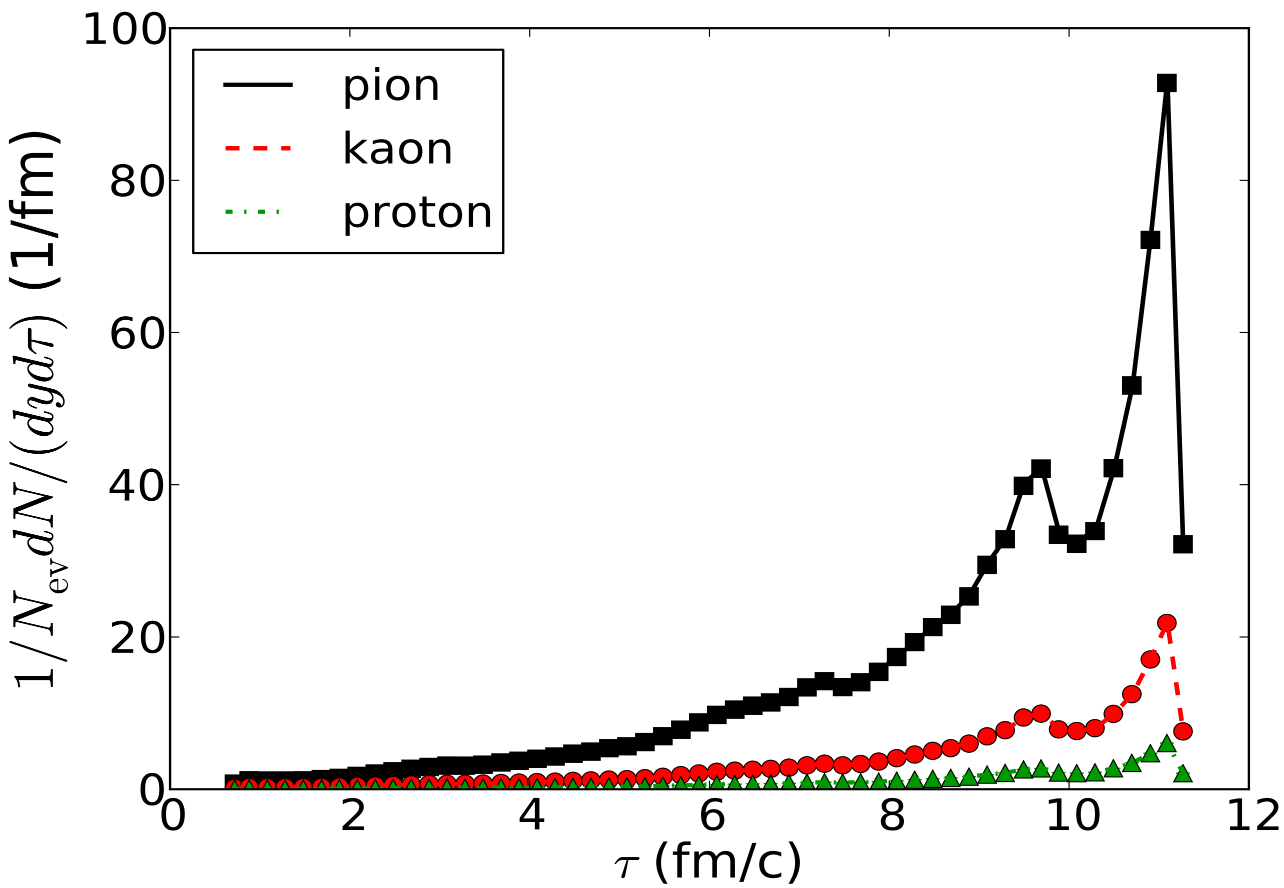
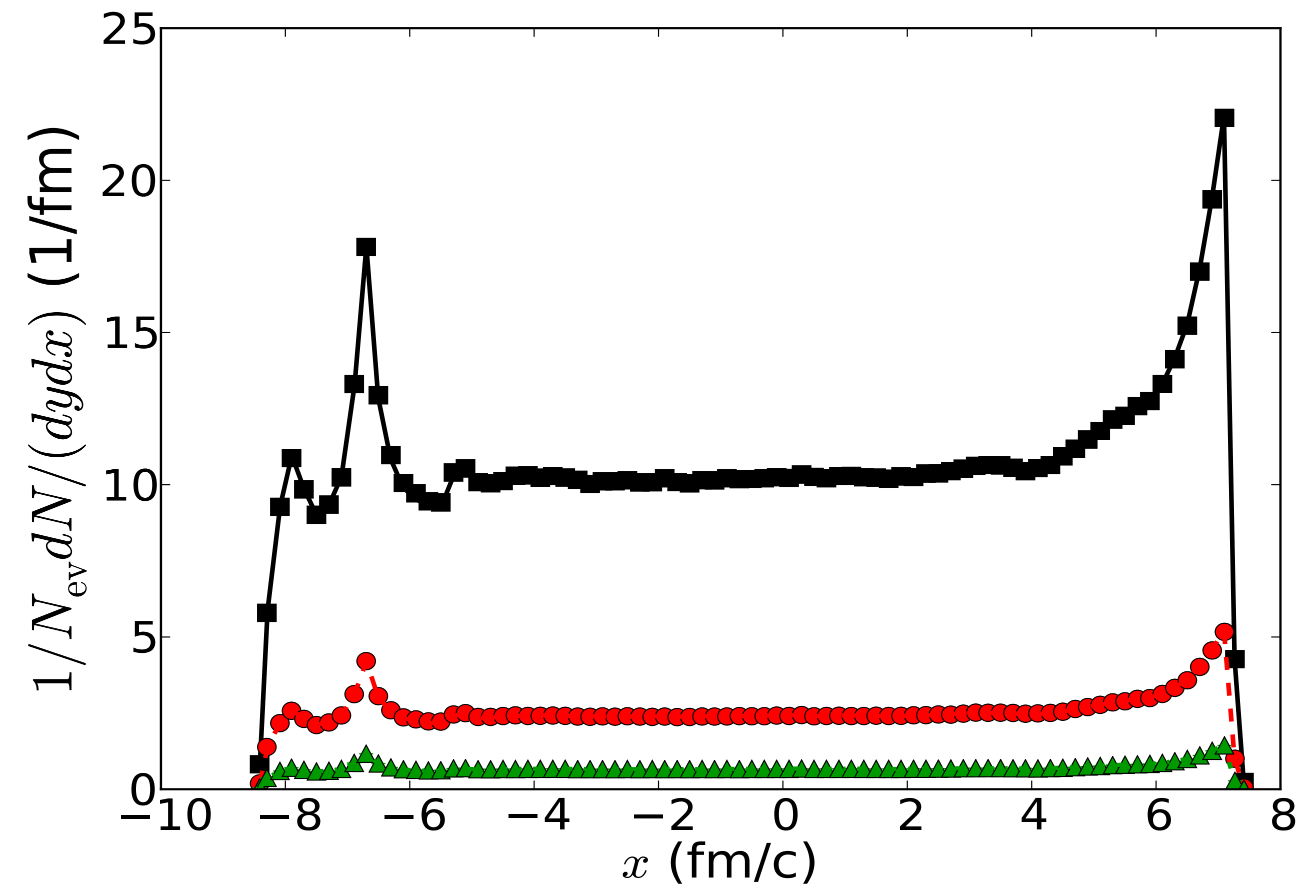
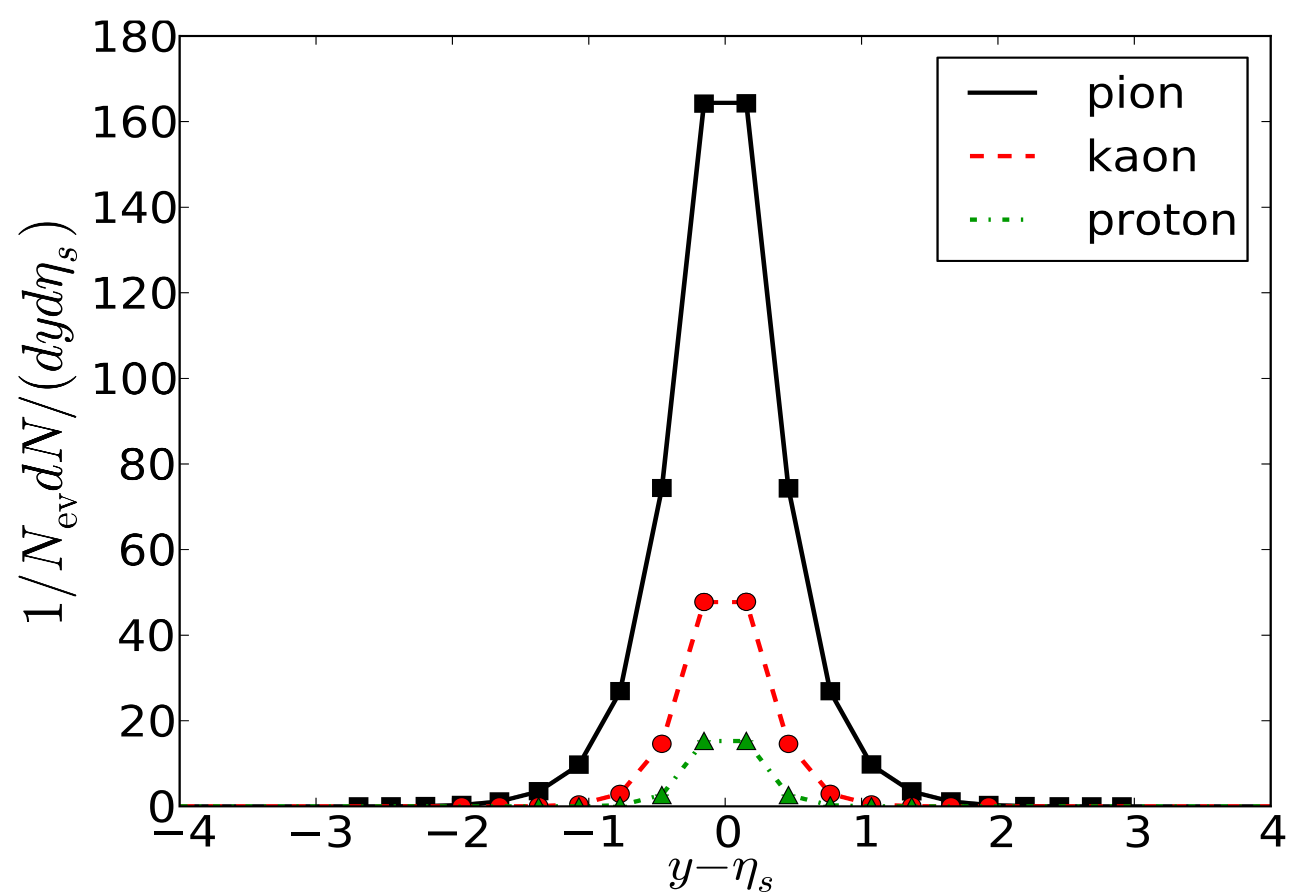






MCKLN 0-40%

$\eta/s = 0.20$

iEBE-JET interface

iEBE-JET interface

OSU-McGill

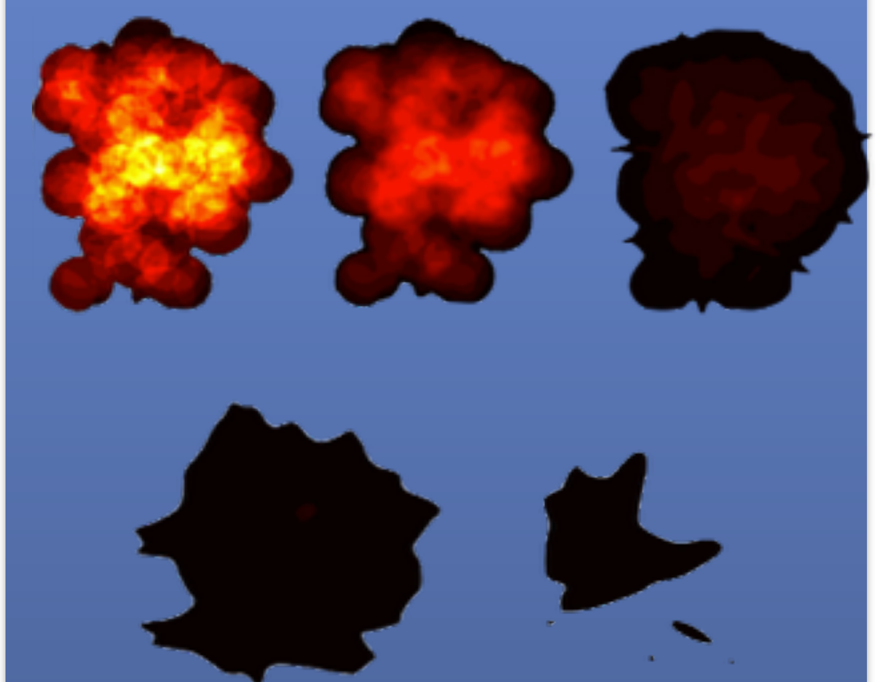
Initial Condition Generators (MC-KLN, MC-Glauber)

https://github.com/chunshen1987/iEBE.git

JET Collaboration

Thermal Photon Emission Rates

Hydrodynamic Simulations (VISH2+1)



HydroInfo Package

$$e, s, p, T, \quad u^\mu, \pi^{\mu\nu}$$

Thermal Photon Interface

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} q_\mu q_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

$$E\frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q}$$

Hadrons spectra & v_n

Photon spectrum & v_n

iEBE-JET interface

OSU-McGill

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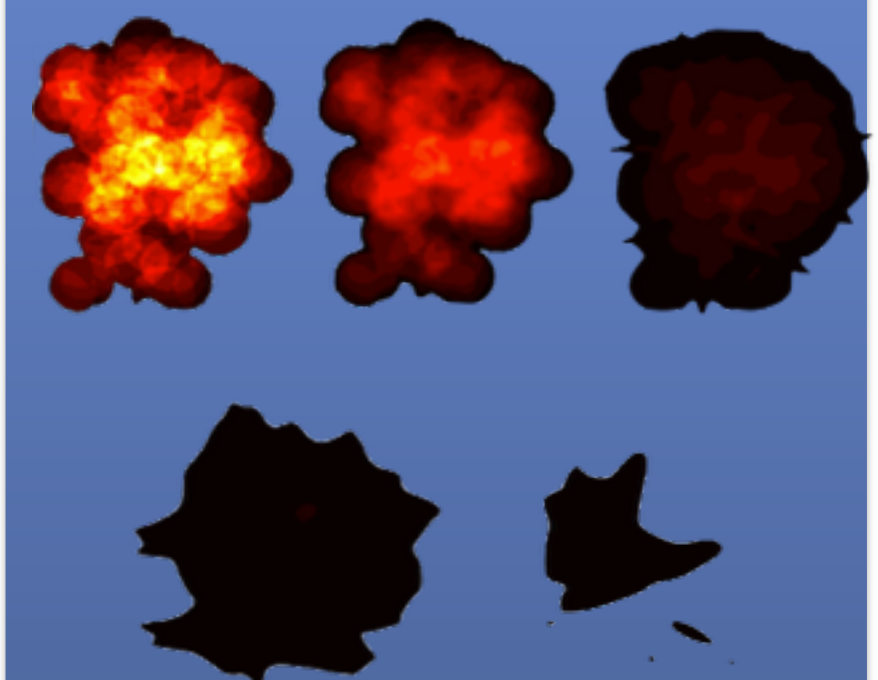
JET Collaboration

Initial Condition Generators (MC-KLN, MC-Glaub…

Thermal Photon Emission Rates

Hydrodynamic Simulations (VISH2+1)

viscous corrections



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$e, s, p, T,$

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Thermal Photon Interface

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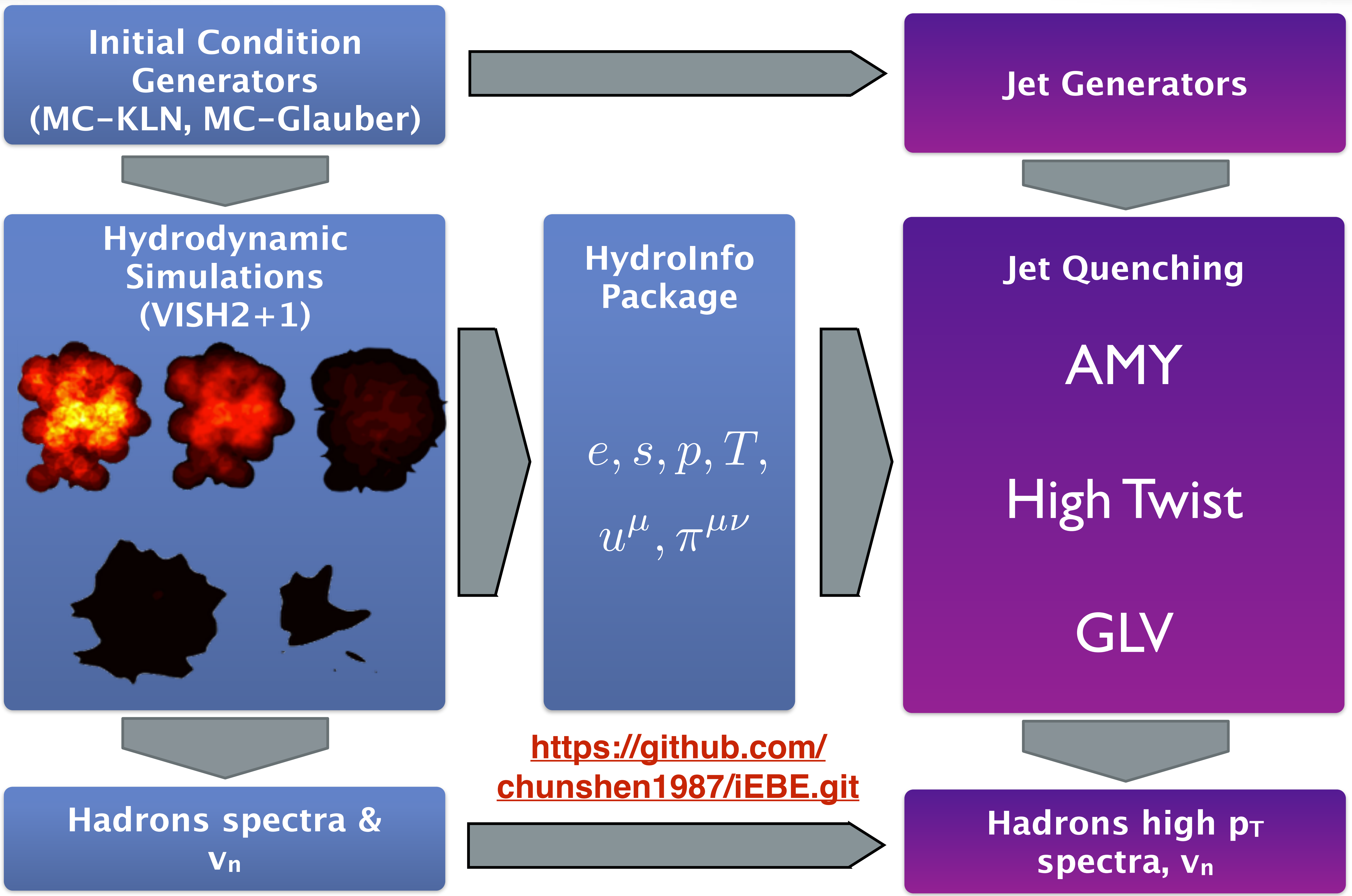
viscous corrections

$$E\frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q}$$

Hadrons spectra & v_n

Photon spectrum & v_n

iEBE-JET interface



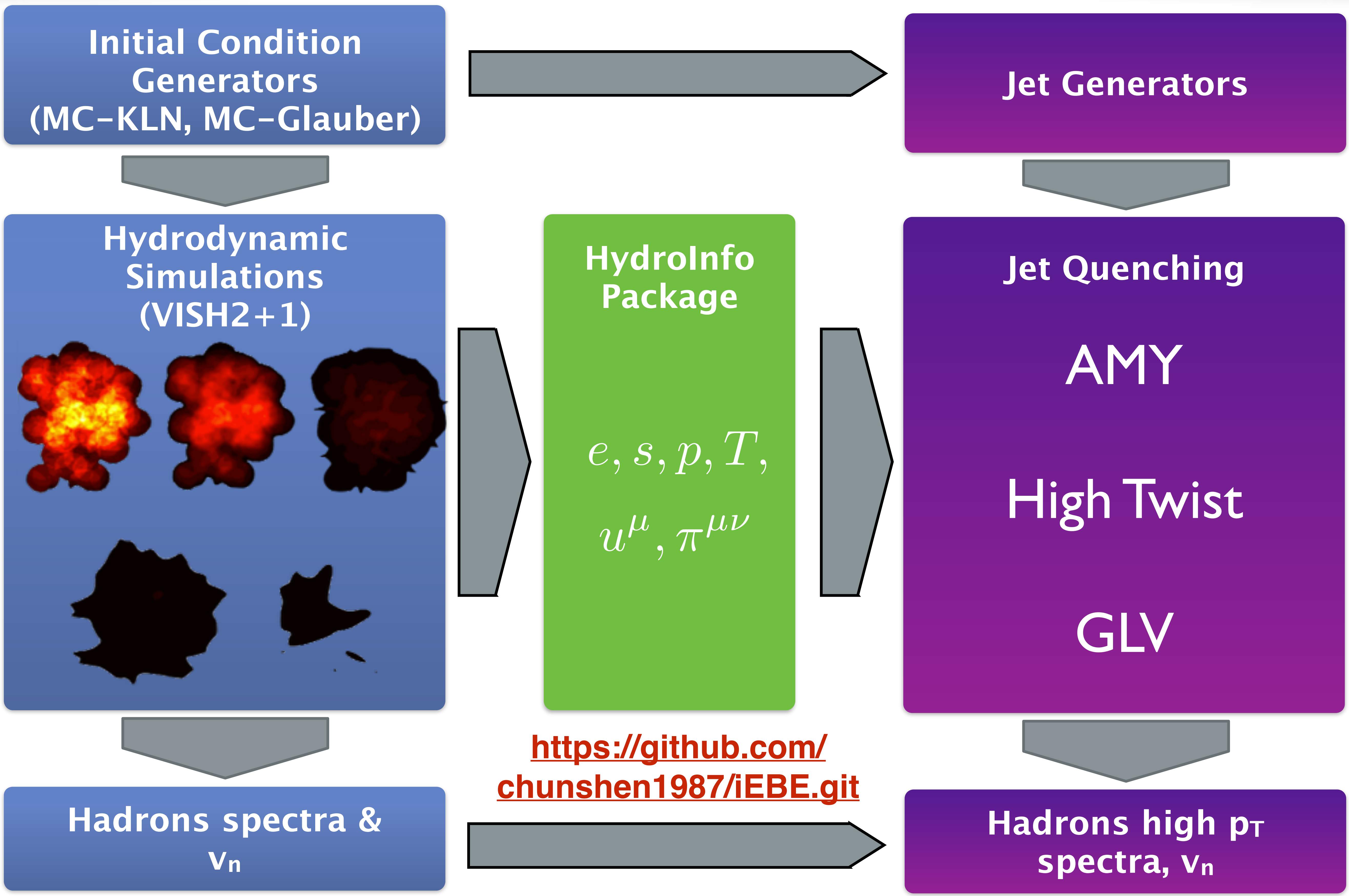
iEBE-JET interface

Our VIP customers:

- ✦ Abhijit (WSU): Jet (HT)
- ✦ Guangyou Qin (CCNU): Jet (AMY)
- ✦ Jiechen Xu (Columbia): Jet (CUJET)
- ✦ Shanshan Cao (Duke): heavy quark
- ✦ Will Horowitz (Cape Town): heavy quark
- ✦ Baoyi Chen (Tsinghua): heavy quark
- ✦ Jonah Bernhard (Duke): Ebe-VISHNU
- ✦ Damir Devetak (CMS): Ebe-VISHNU

- ✤ Min He (NUST), Zhou You (ALICE), Chiho (Nagoya), Jingfeng Liao (Indiana)

iEBE-JET interface



Hydroinfo package

Hydrodynamics evolves energy stress tensor,

$T^{\mu\nu}$

$e(\mathrm{GeV/fm^3})$ $s(1/\mathrm{fm^3})$ $p(\mathrm{GeV/fm^3})$

$T(\mathrm{GeV})$ u^μ

$\pi^{\mu\nu}(\mathrm{GeV/fm^3})$ $\Pi(\mathrm{GeV/fm^3})$ (optional)

HDF5 Format (Hierarchical Data Format)

- Binary format

  typically 8 times smaller than text file

- Fast random access

  very handy for future MC jet quenching

- Platform independent (Mac, Linux, and Windows)
- Compatible with lots of languages and softwares

  C++, **Fortran**, Matlab, Mathematica, ...

- Friendly GUI (easy to check data)

http://www.hdfgroup.org/HDF5/

Interface Example

Initialization:

```
int bufferSize = paraRdr->getVal("HydroinfoBuffersize");
int hydroInfoVisflag = paraRdr->getVal("HydroinfoVisflag");
HydroinfoH5* hydroinfo_ptr = new HydroinfoH5("results/JetData.h5",
bufferSize, hydroInfoVisflag);    //hydro data file pointer
int neta = paraRdr->getVal("neta");
```

Get hydro information:

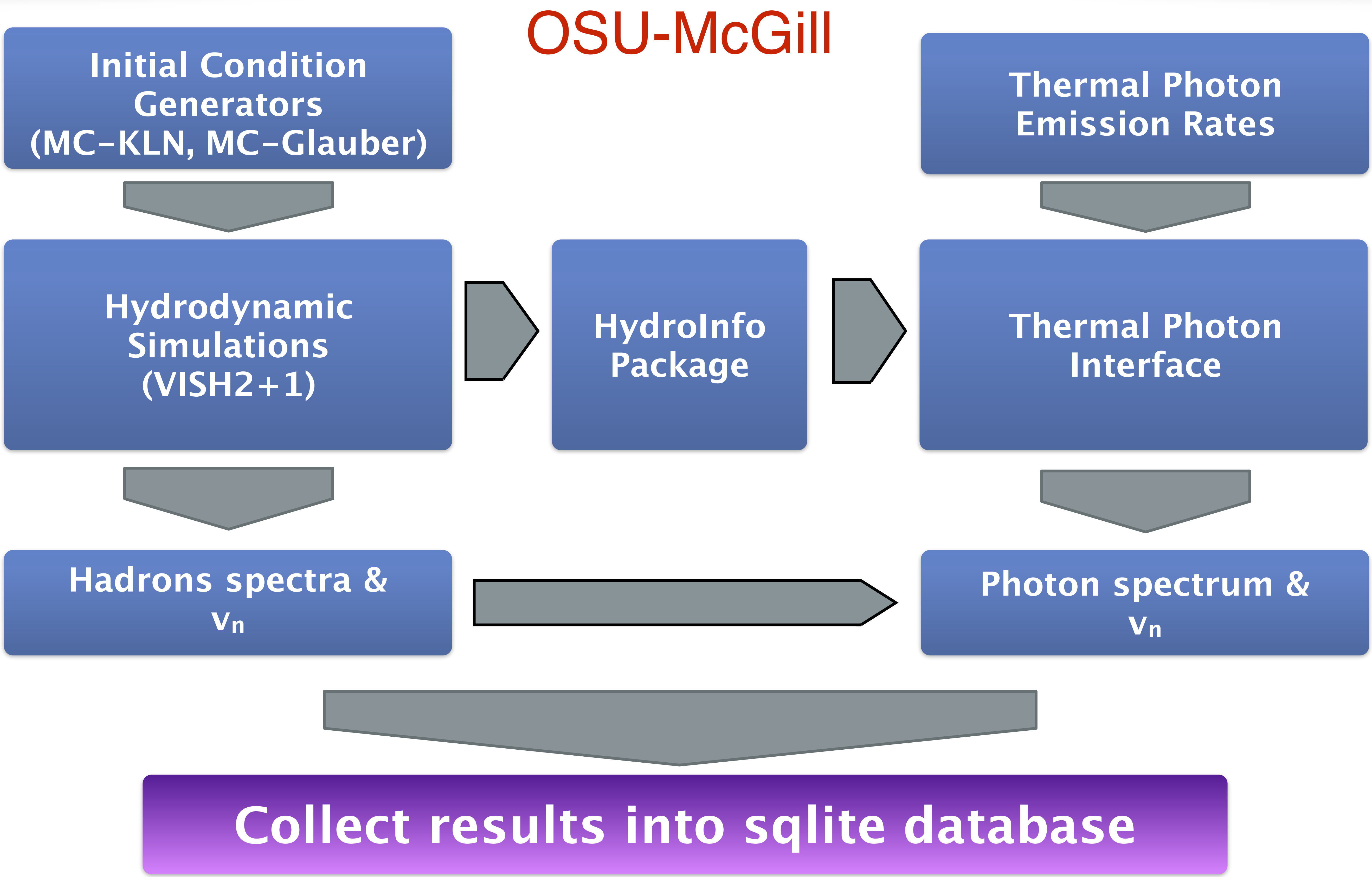
```
int idx_Tb = 0;
hydroinfo_ptr->getHydroinfo(tau_local, x_local, y_local, fluidCellptr);
temp_local = fluidCellptr->temperature;
```

Hydrodynamic variables at
tau_local, x_local, y_local

```

struct fluidCell {
    double ed, sd, vx, vy,
           temperature, pressure;
    double pi[4][4];
    double bulkPi;
};
```

iEBE-JET package



Viscous Photon Emission Rates: General Formalism

Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |\mathcal{M}|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \frac{\pi^{\mu\nu} \hat{p}_\mu \hat{p}_\nu}{2(e+p)} \chi\left(\frac{p}{T}\right)$$

We can expand photon emission rates around the thermal equilibrium:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} \hat{q}_\mu \hat{q}_\nu}{2(e+p)} a_{\alpha\beta} \Gamma^{\alpha\beta},$$

OSU-McGill

$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4} \hat{q}_\mu \hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2} u_\mu u_\nu + \frac{1}{2(u\cdot\hat{q})^2} g_{\mu\nu} - \frac{3}{2(u\cdot\hat{q})^3} (\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

Viscous Photon Emission Rates: General Formalism

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$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = \ldots \frac{\pi^{\mu\nu}\hat{p}_\mu\hat{p}_\nu}{\ldots)} \chi\left(\frac{p}{T}\right)$$

$\Gamma_0(q,T)$ $a_{\alpha\beta}\Gamma^{\alpha\beta}(q,T)$

calculated in fluid local rest frame

We can expa... ...und the thermal equilibrium:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta},$$

OSU-McGill

calculated in lab frame

$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{\ldots}{2(u\cdot\hat{q})^2} \ldots \mu).$$

Viscous Photon Emission Rates: General Formalism

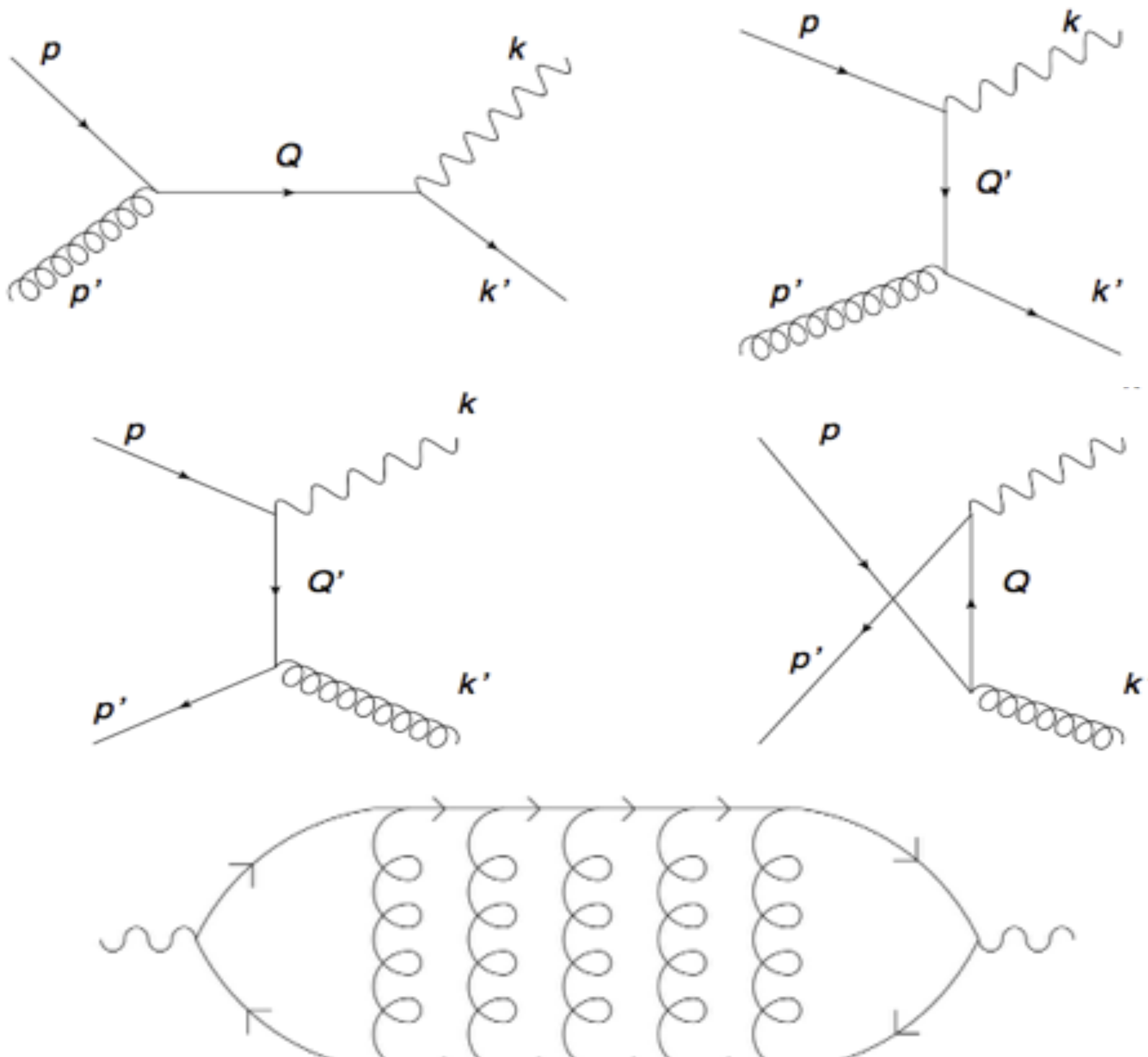
$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)}a_{\alpha\beta}\Gamma^{\alpha\beta}$$

OSU-McGill

Equilibrium rates

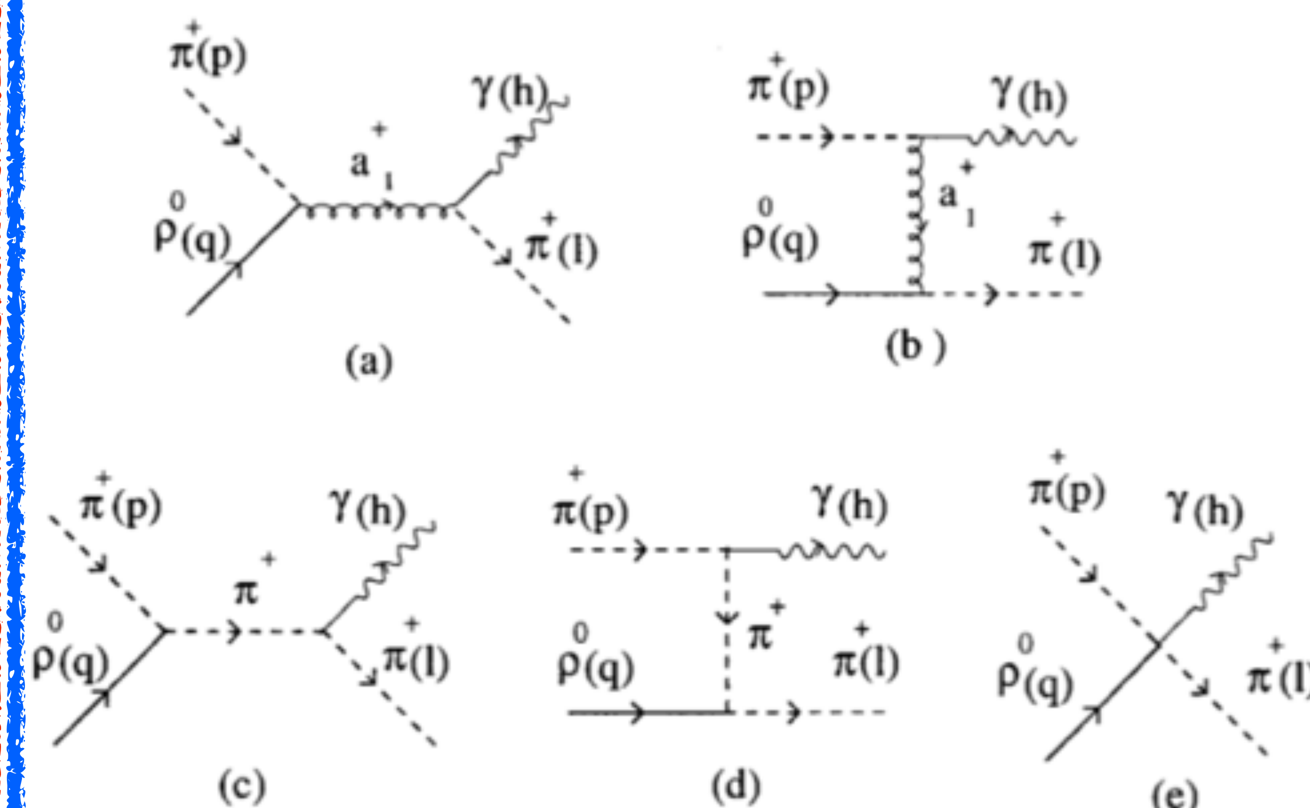
QGP

(AMY 2001)



Hadron Gas

(TRG 2004)



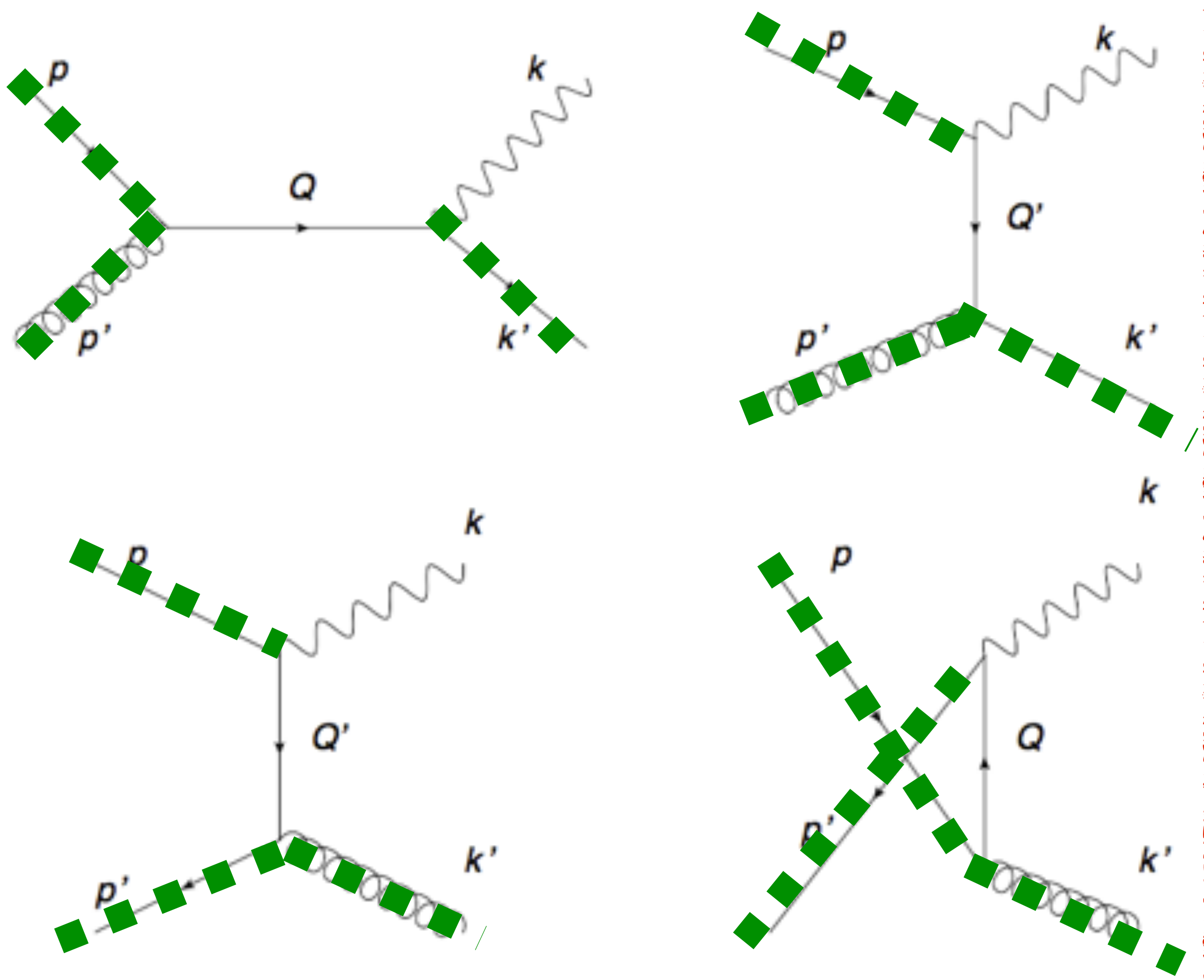
Viscous Photon Emission Rates: General Formalism

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

OSU-McGill

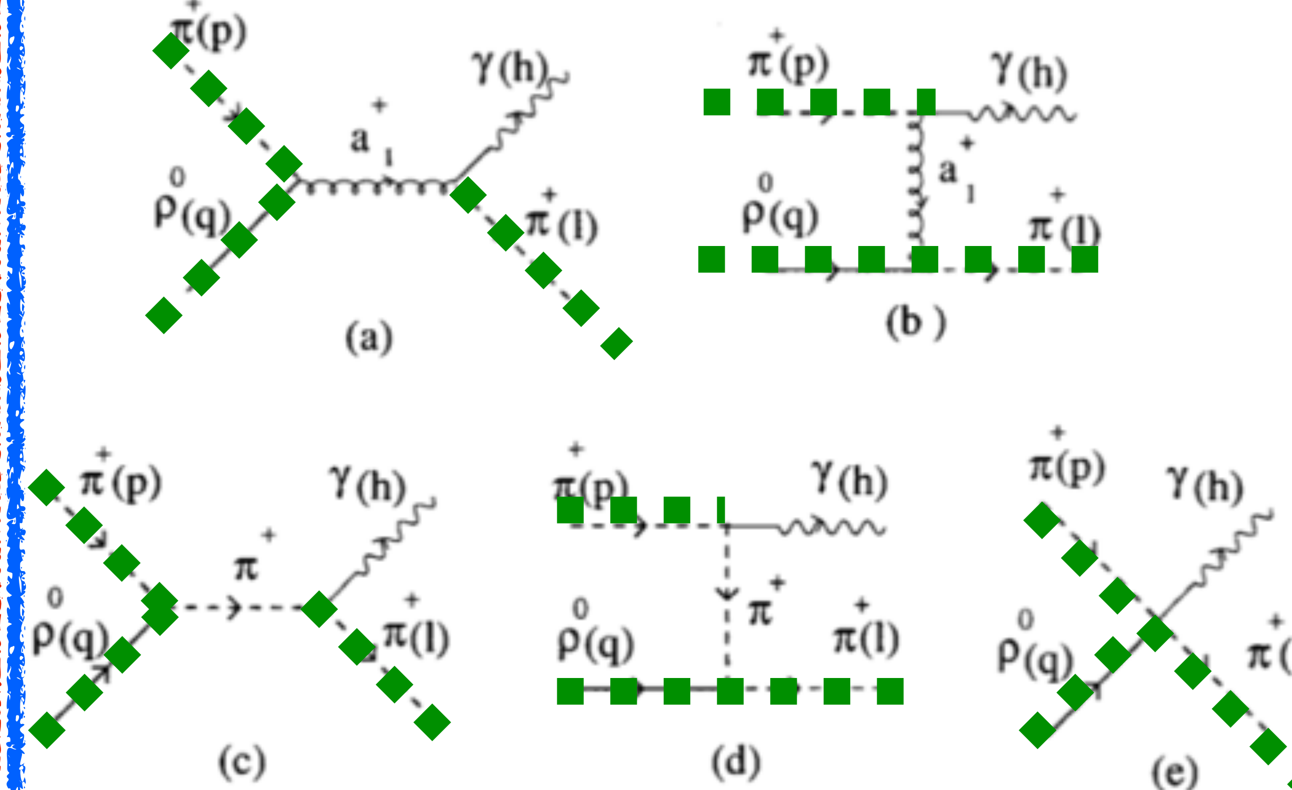
Equilibrium rates — off-equilibrium δf corrections

QGP



Dusling NPA839 (2010) 70

Hadron Gas



Dion et al. PRC84 (2011) 064901

Viscous Photon Emission Rates: General Formalism

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)}a_{\alpha\beta}\Gamma^{\alpha\beta}$$

OSU-McGill

Equilibrium rates — off-equilibrium δf corrections

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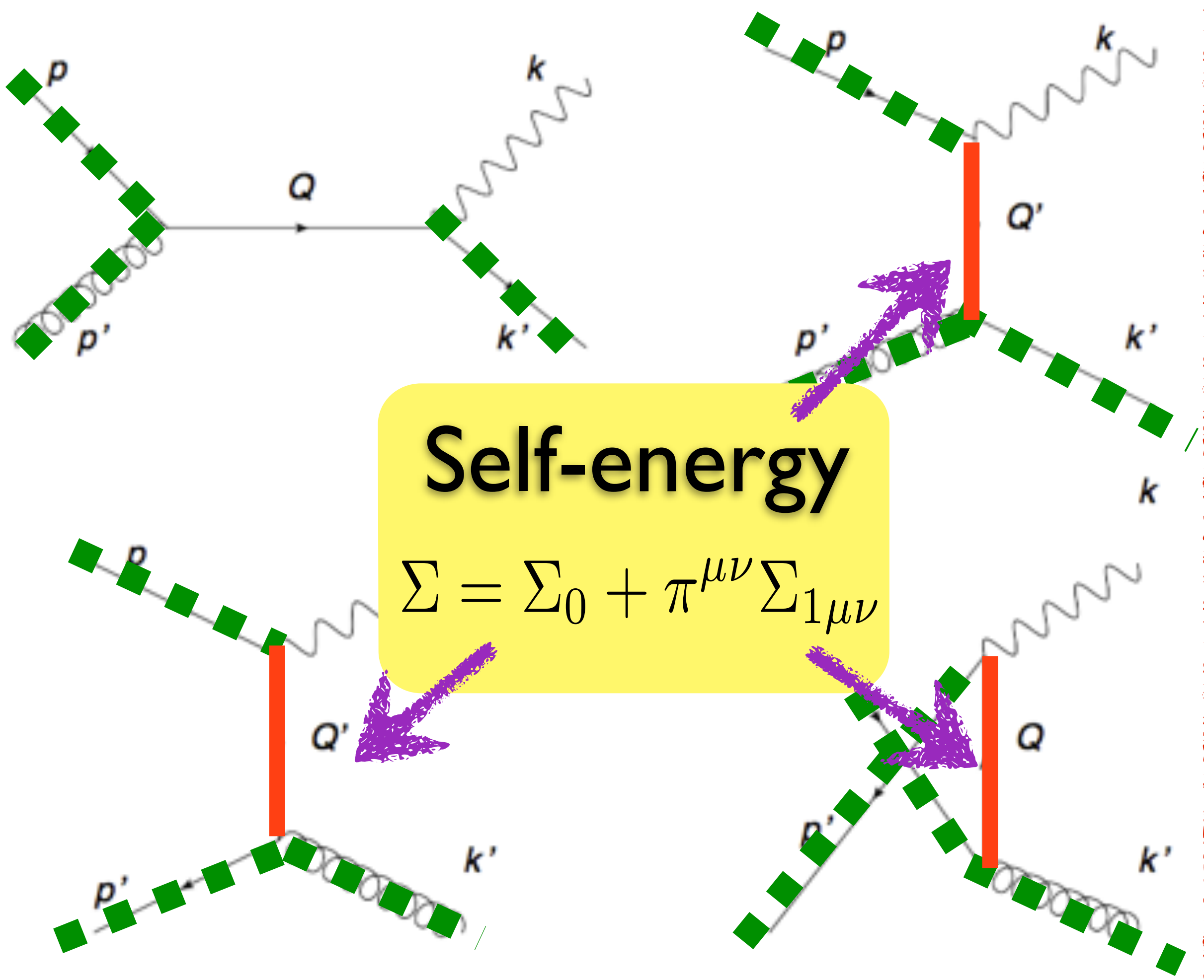
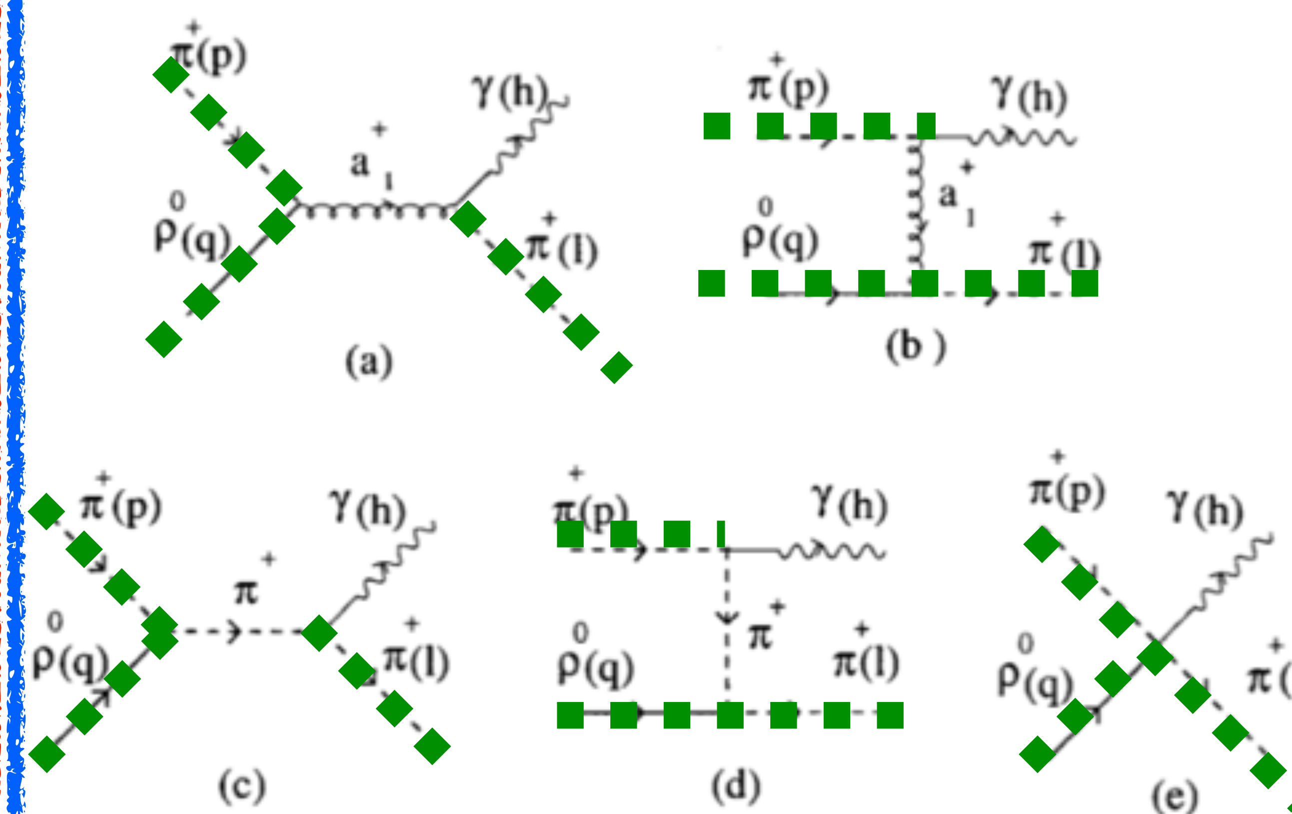
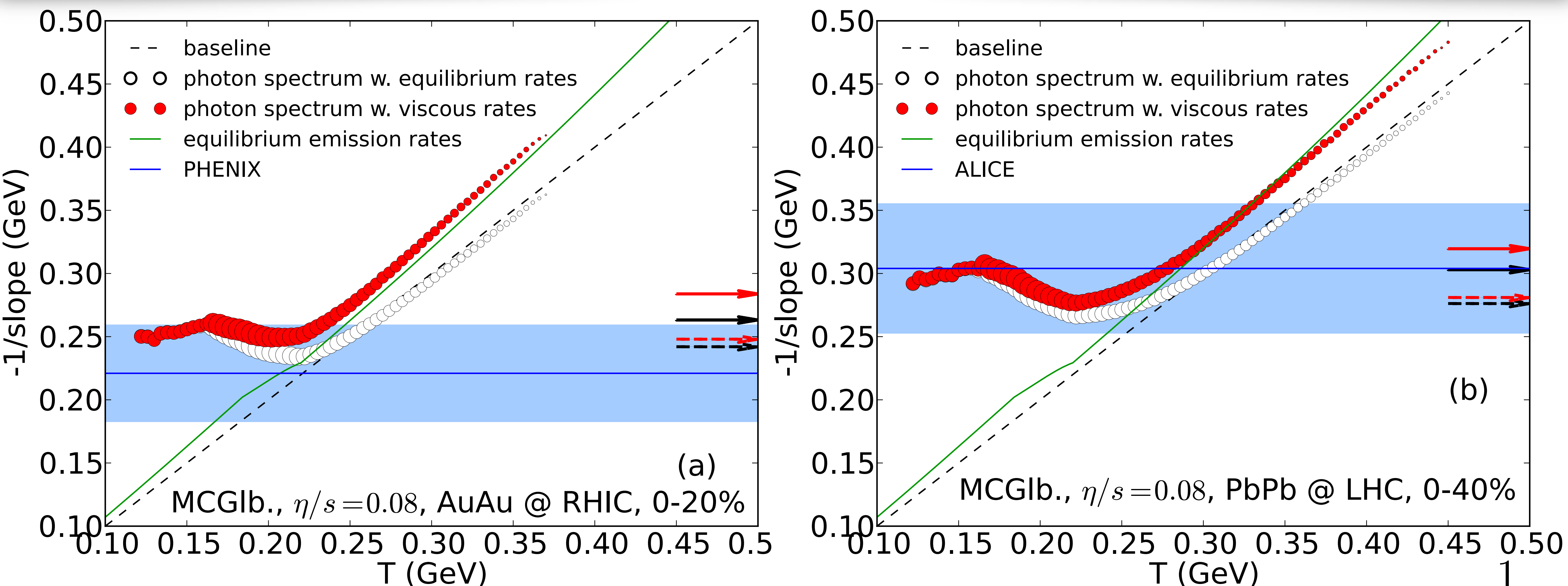


Shen, Paquet et al. (2014)

Hadron Gas



Fitted T_{eff} vs. True Temperature

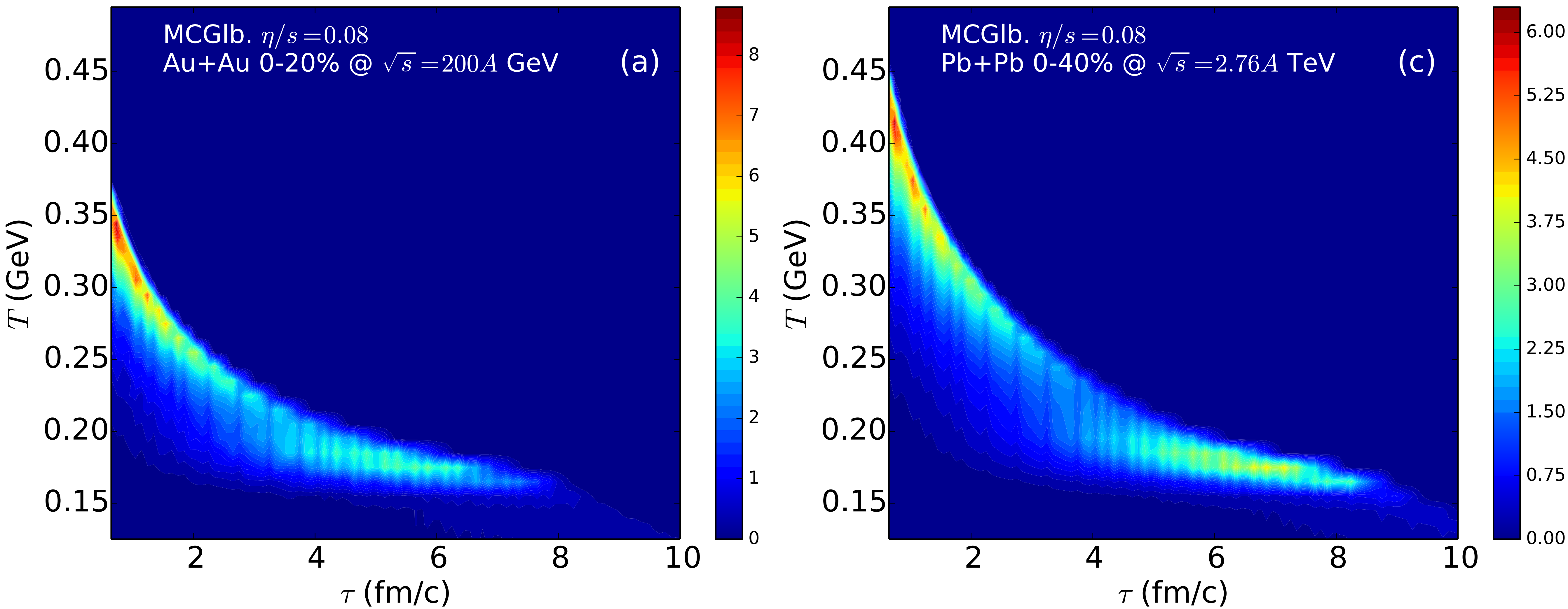


$$T_{\mathrm{eff}} = -\frac{1}{\mathrm{slope}}$$

- Photon emission rates $\propto \exp(-E/T)\log(E/T)$, $T_{\mathrm{eff}} > T$
- **All** photons with T < 250 MeV at RHIC and < 300 MeV at LHC carries T_{eff} within the experimental fitted region
- About **50-60%** of photons are emitted from T = 165~250 MeV, they are strongly blue shifted by radial flow

$$T_{\mathrm{eff}} = T\sqrt{\frac{1+v}{1-v}}$$

Mapping thermal photon emission

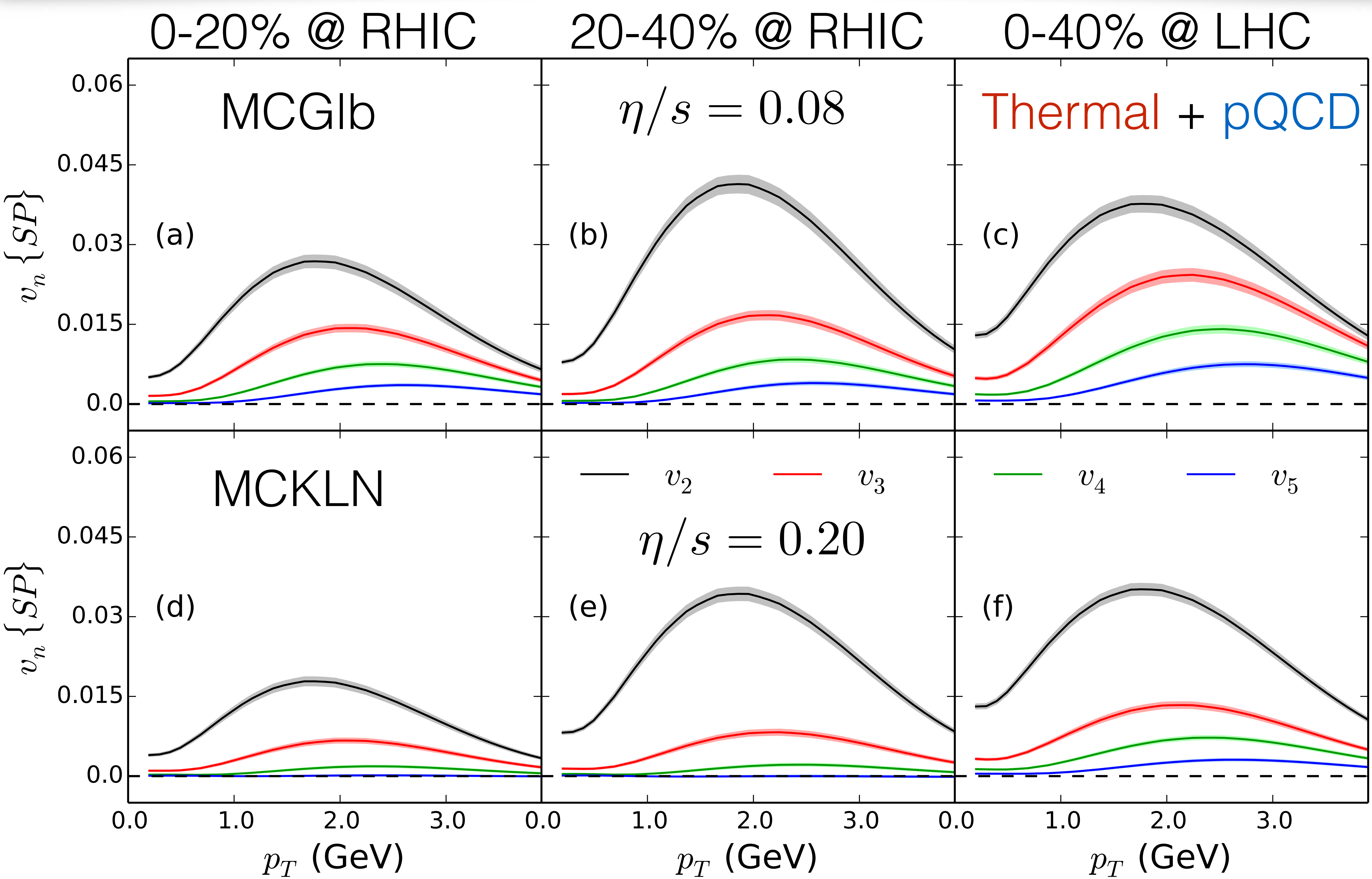


- By cutting hydro medium both in T and tau, we observe a **two-wave** thermal photon production

early time production — high rates at high temperatures

near transition region — growing of space-time volume

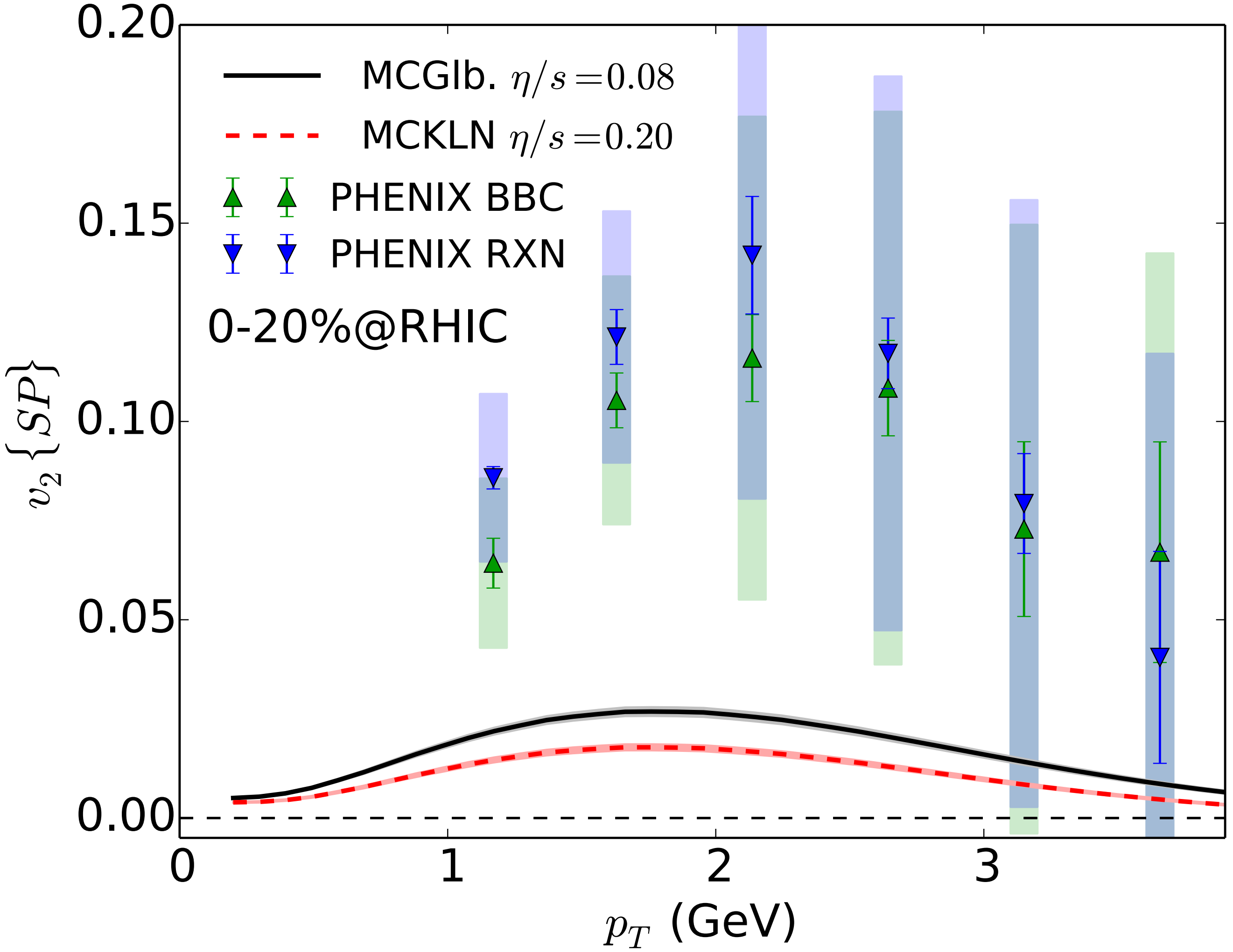
Event-by-Event Full Viscous Photon v_n



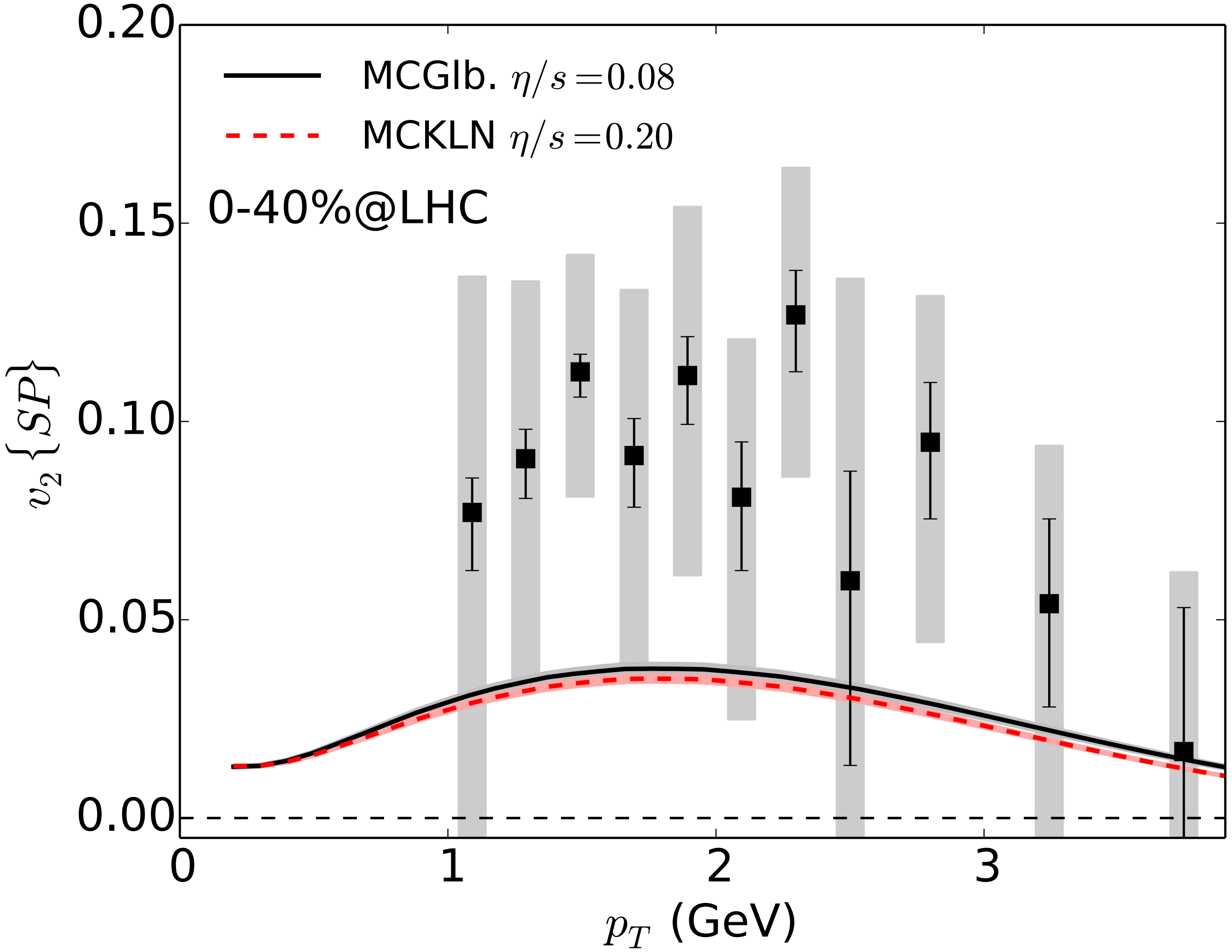
arXiv: 1308.2111

Comparisons with exp. data

RHIC 0-20%



LHC 0-40%

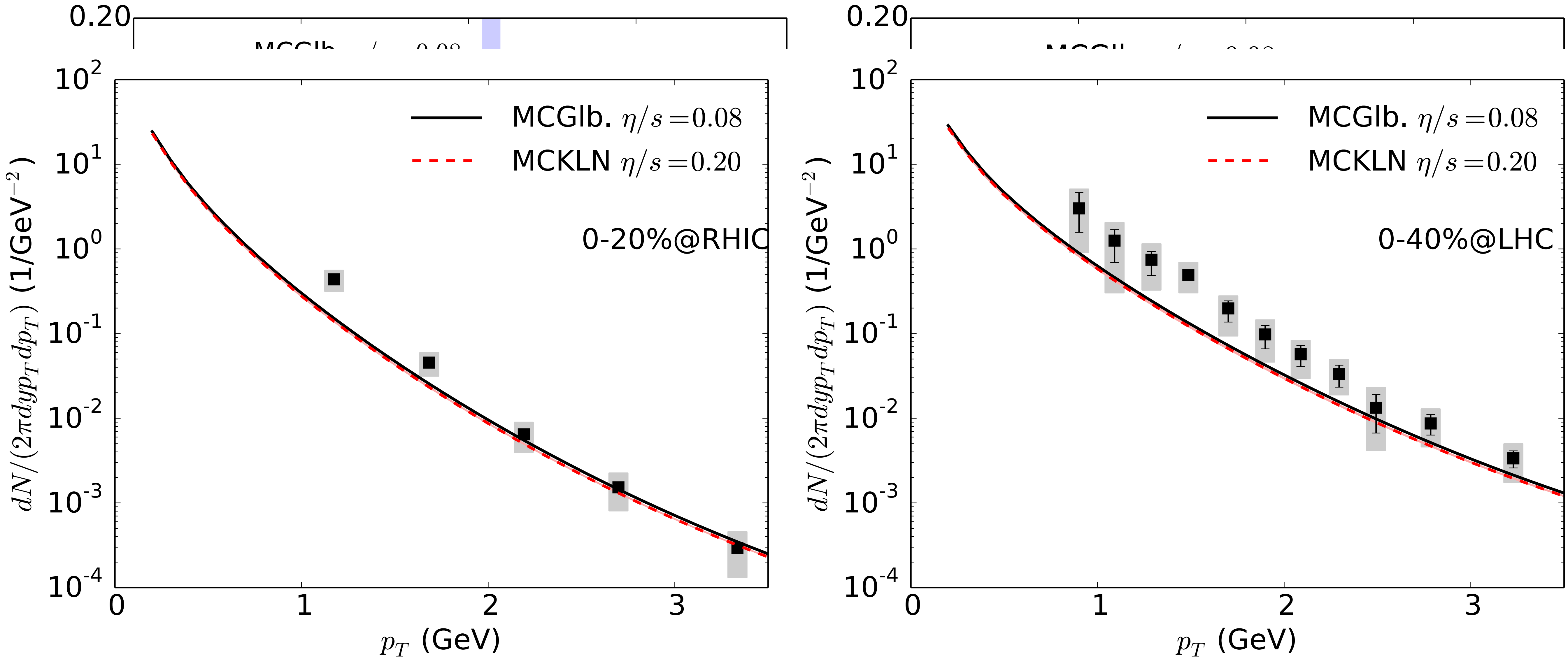


- Current calculations still underestimate the experimental data by a factor of 3

arXiv: 1308.2111

Comparisons with exp. data

RHIC 0-20% **LHC 0-40%**



- Current calculations still underestimate the experimental data by a factor of 3
- Thermal yield is also missing in the azimuthally integrated photon spectra at low p_T

arXiv: 1308.2111

EM decays of short-lived resonances (I)

Thanks to Ralf Rapp and EMMI RRTF

Contributions from the short-lived resonances:

reaction	branching ratio
$\rho^0 \to \pi^+ + \pi^- + \gamma$	1%
$b_1(1235) \to \pi^\pm + \gamma$	$1.6 * 10^{-3}$
$h_1(1170) \to \pi^0 + \gamma$	$1.7 * 10^{-3}$
$a_1(1260) \to \pi^0 + \gamma$	$1.7 * 10^{-3}$
$f_1(1285) \to \rho_0 + \gamma$	5.5%
$a_2(1320) \to \pi^\pm + \gamma$	$2.68 * 10^{-3}$
$K^*(892) \to K^0 + \gamma$	$2.4 * 10^{-3}$
$K^*(892) \to K^\pm + \gamma$	$1 * 10^{-3}$
$K_1(1270) \to K^0 + \gamma$	$8.4 * 10^{-4}$
$K_1(1400) \to K^0 + \gamma$	$1.6 * 10^{-3}$
$K_2^*(1430) \to K^+ + \gamma$	$2.4 * 10^{-3}$
$K_2^*(1430) \to K^0 + \gamma$	$9 * 10^{-4}$

reaction	branching ratio
$N(1440) \to p + \gamma$	$4.15 * 10^{-4}$
$N(1440) \to n + \gamma$	$3 * 10^{-4}$
$N(1520) \to p + \gamma$	$4.15 * 10^{-3}$
$N(1520) \to n + \gamma$	$4.15 * 10^{-3}$
$N(1530) \to p + \gamma$	$2.25 * 10^{-3}$
$N(1530) \to n + \gamma$	$2.25 * 10^{-3}$
$N(1650) \to p + \gamma$	$1.2 * 10^{-3}$
$N(1650) \to n + \gamma$	$8.5 * 10^{-4}$
$N(1675) \to p + \gamma$	$1 * 10^{-4}$
$N(1675) \to n + \gamma$	$7.5 * 10^{-4}$
$N(1680) \to p + \gamma$	$2.65 * 10^{-3}$
$N(1680) \to n + \gamma$	$3.35 * 10^{-4}$
$N(1700) \to p + \gamma$	$3 * 10^{-4}$
$N(1700) \to n + \gamma$	$1.2 * 10^{-3}$
$N(1710) \to p + \gamma$	$4.1 * 10^{-4}$
$N(1710) \to n + \gamma$	$1 * 10^{-4}$
$N(1720) \to p + \gamma$	$1.5 * 10^{-3}$
$N(1720) \to n + \gamma$	$8 * 10^{-5}$

$\Delta(1232) \to N + \gamma$	0.6%
$\Delta(1600) \to N + \gamma$	$1.8 * 10^{-4}$
$\Delta(1620) \to N + \gamma$	$6.5 * 10^{-4}$
$\Delta(1700) \to N + \gamma$	$4.1 * 10^{-3}$
$\Delta(1905) \to N + \gamma$	$2.4 * 10^{-4}$
$\Delta(1910) \to N + \gamma$	$1 * 10^{-4}$
$\Delta(1920) \to N + \gamma$	$2 * 10^{-3}$
$\Delta(1950) \to N + \gamma$	$1.05 * 10^{-3}$

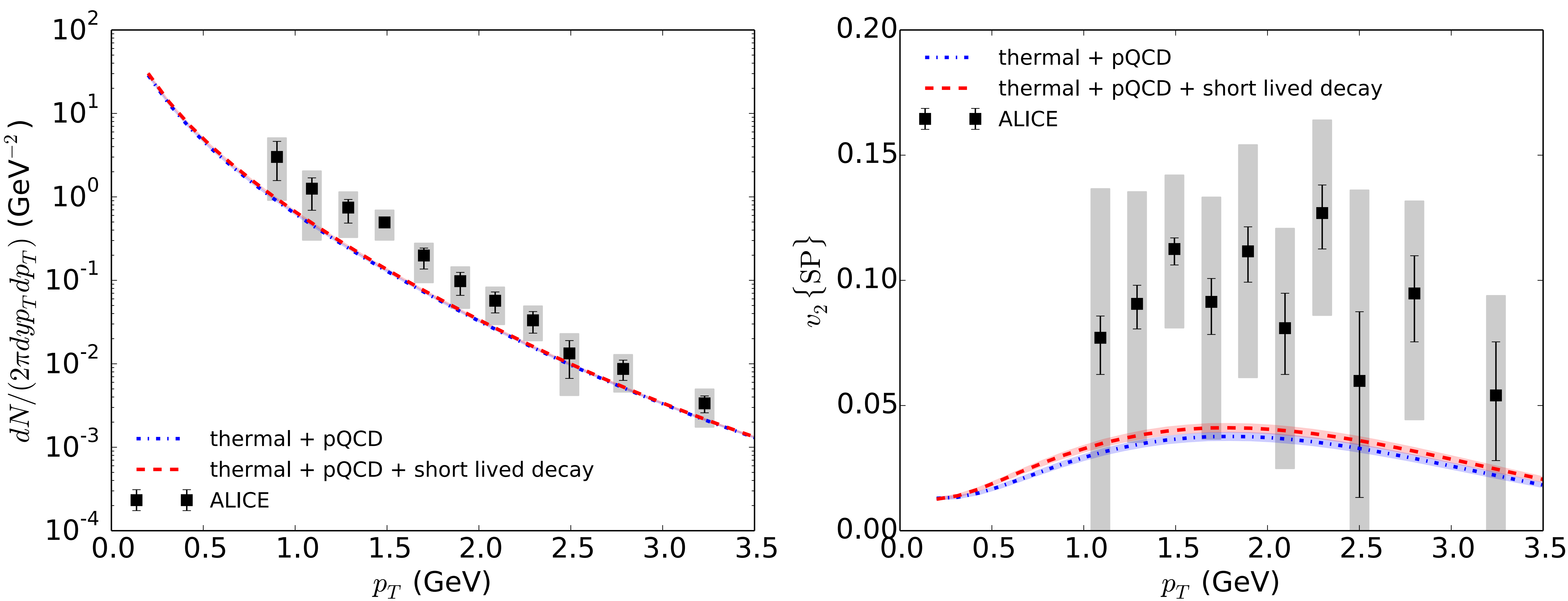
reaction	branching ratio
$\Lambda(1405) \to \Lambda + \gamma$	$5.4 * 10^{-4}$
$\Lambda(1405) \to \Sigma^0 + \gamma$	$2 * 10^{-4}$
$\Lambda(1520) \to \Lambda + \gamma$	$8.5 * 10^{-3}$
$\Lambda(1520) \to \Sigma^0 + \gamma$	2%
$\Sigma^0(1385) \to \Lambda + \gamma$	1.25%
$\Xi(1530) \to \Xi + \gamma$	4%

EM decays of short-lived resonances (II)

Thanks to Ralf Rapp and EMMI RRTF

Contributions from the short-lived resonances:

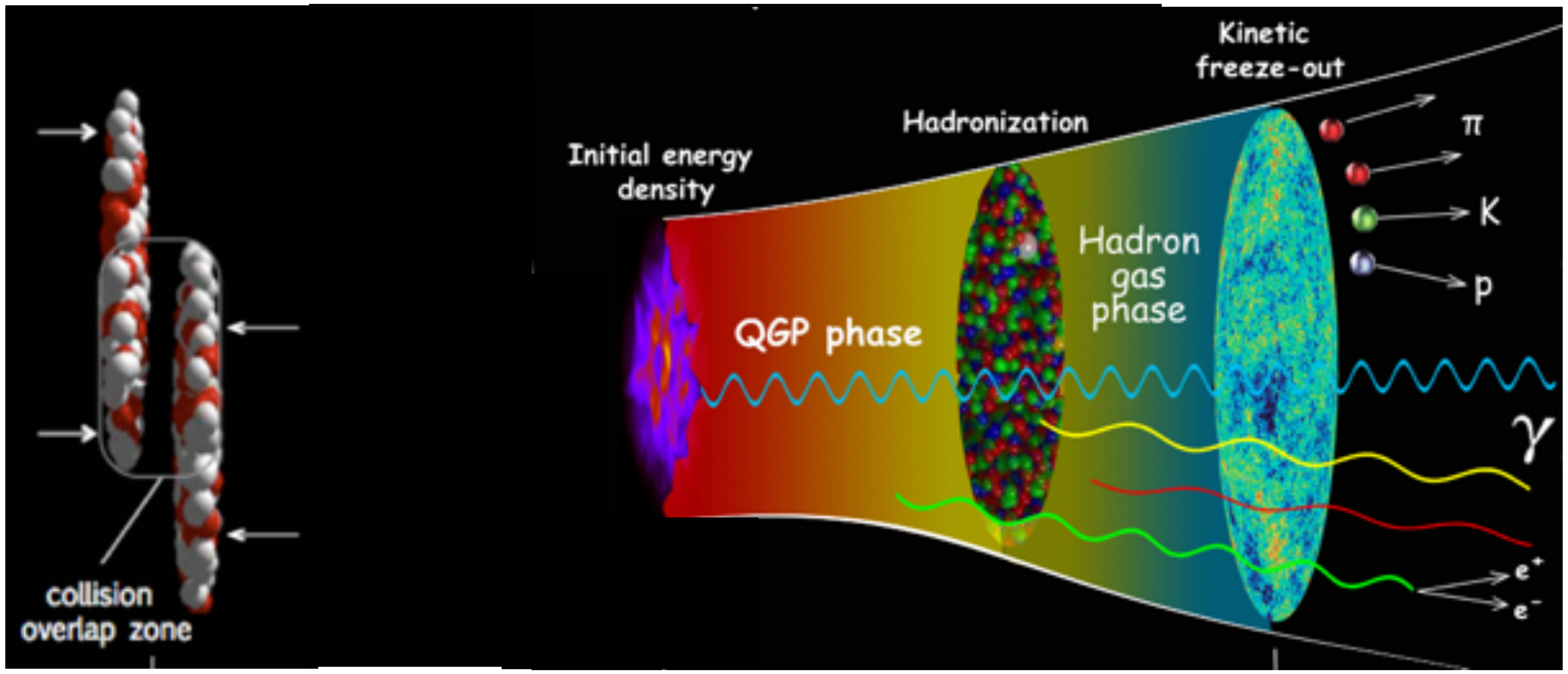
reaction	branching ratio	reaction	branching ratio		
				$\Delta(1232) \to N + \gamma$	0.6%
		$N(1700) \to n + \gamma$	$1.2 * 10^{-3}$	$\Lambda(1520) \to \Sigma^0 + \gamma$	2%
		$N(1710) \to n + \gamma$	$1 * 10^{-4}$	$\Xi(1530) \to \Xi + \gamma$	4%
		$N(1720) \to p + \gamma$	$1.5 * 10^{-3}$		
		$N(1720) \to n + \gamma$	$8 * 10^{-5}$		



Small but significant effects in the right direction

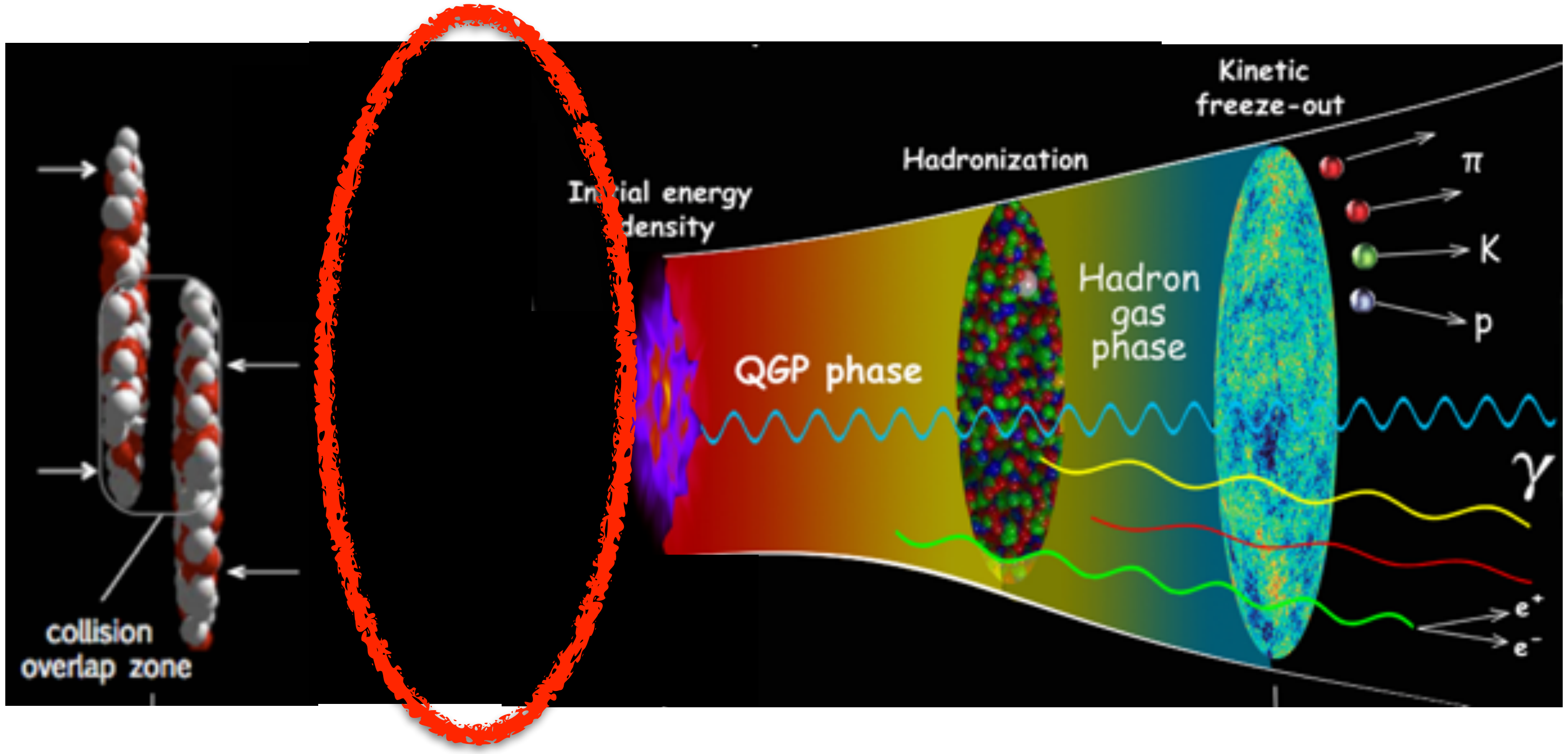
Pre-equilibrium flow (I)

Contributions from pre-equilibrium flow and $\pi^{\mu\nu}$:



Pre-equilibrium flow (II)

Contributions from pre-equilibrium flow and $\pi^{\mu\nu}$:



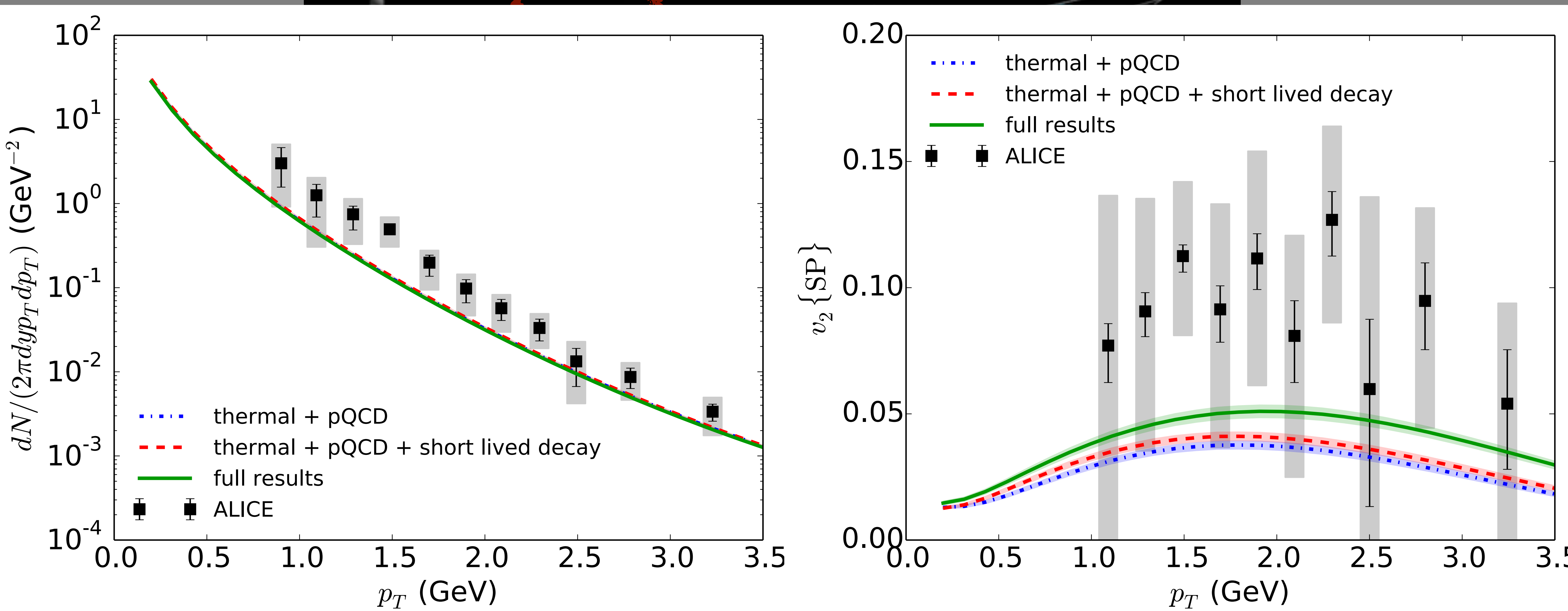
Free-streaming $f(\tau_s, \vec{x}, \vec{p}) = f(\tau_0, \vec{x} - \hat{\vec{p}}(\tau_s - \tau_0), \vec{p})$

$$T^{\mu\nu}(\tau_s, \vec{x}) = \int \frac{d^3p}{E} p^\mu p^\nu f(\tau_s, \vec{x}, p)$$

$$T^{\mu\nu} u_\nu = e u^\mu \rightarrow = e u^\mu u^\nu - (P + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}$$

Pre-equilibrium flow (III)

Contributions from pre-equilibrium flow and $\pi^{\mu\nu}$:



Small but significant effects in the right direction

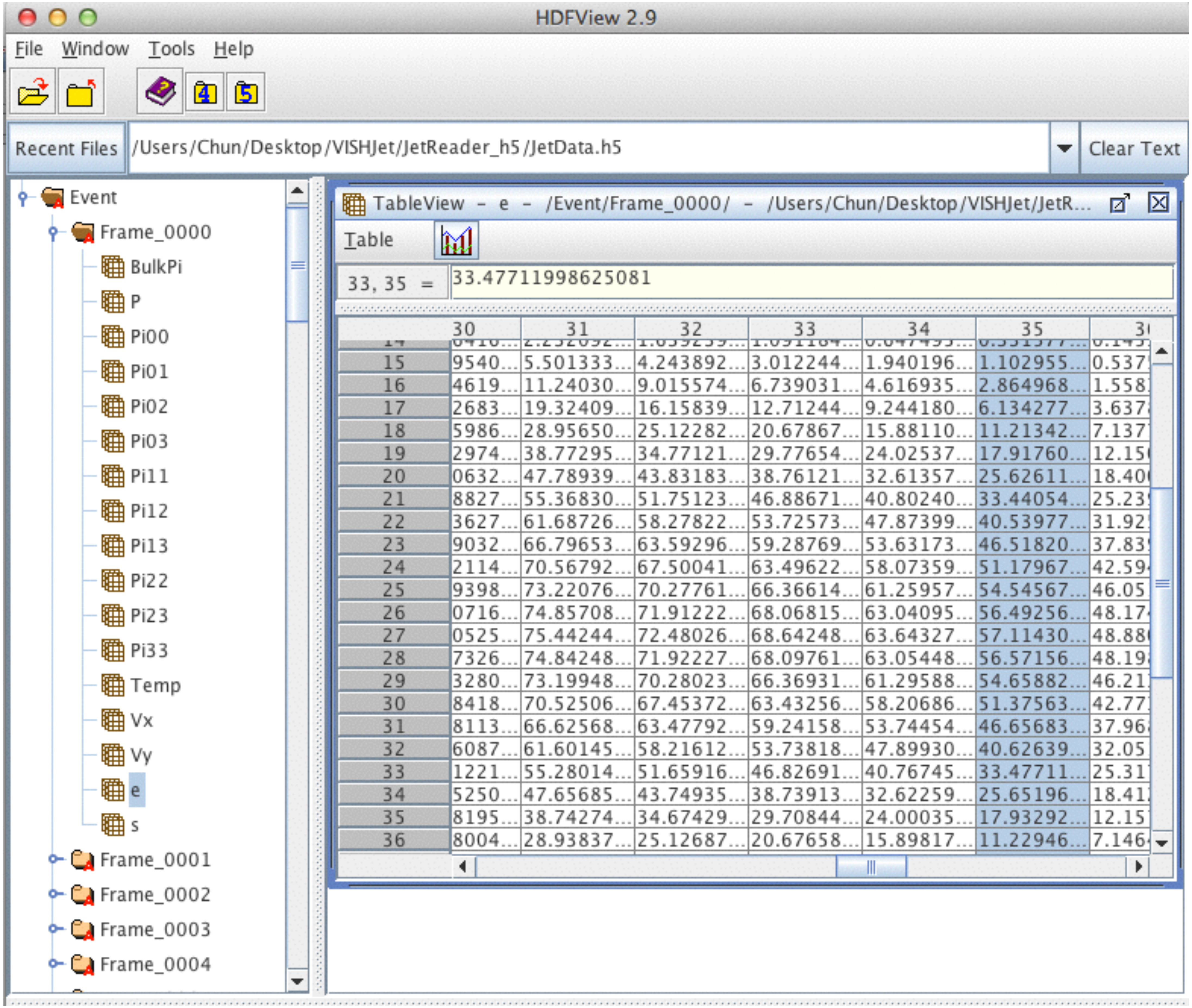
Conclusion and outlook

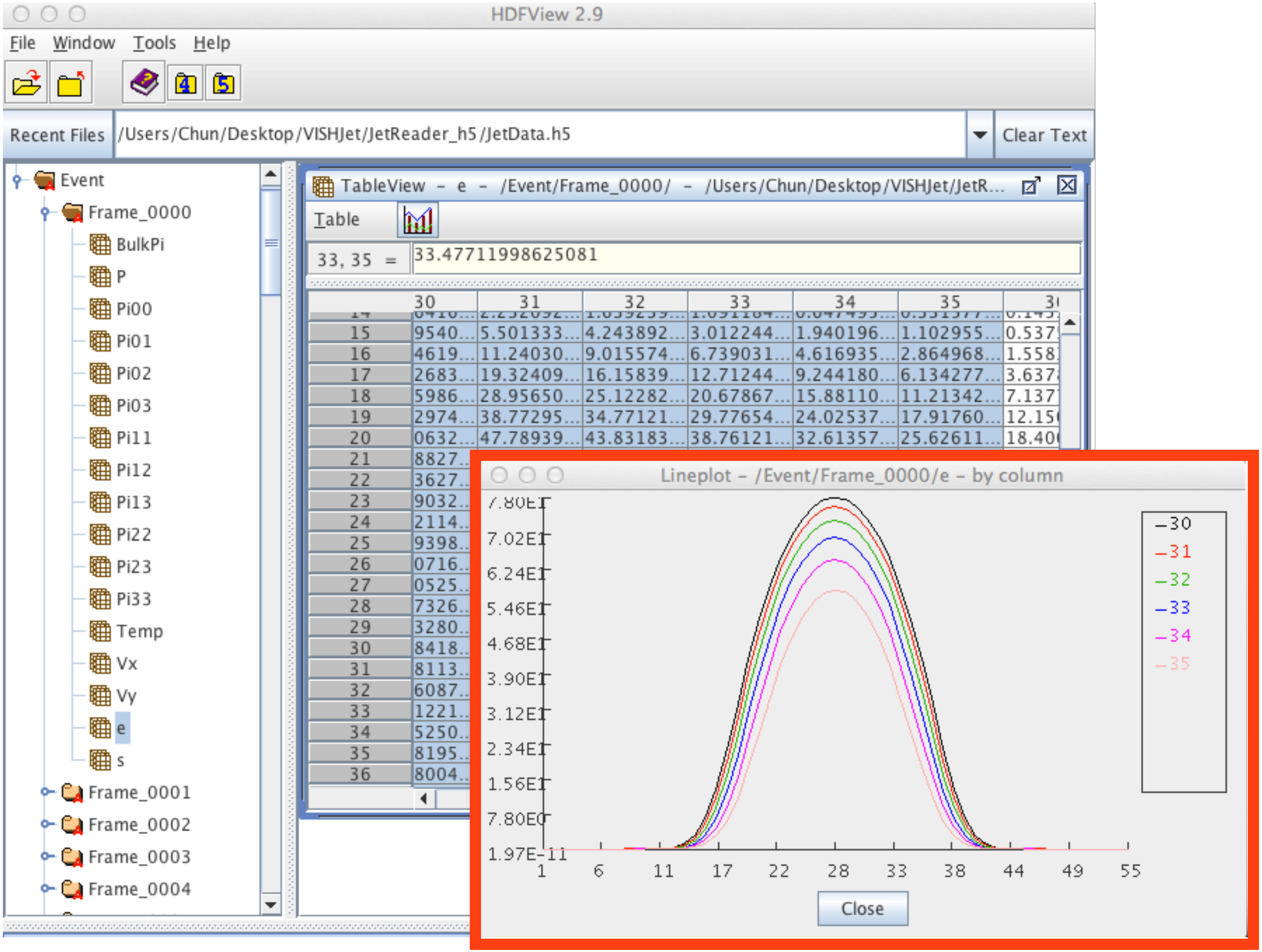
- iEBE provides an advanced model framework to describe the bulk dynamics of relativistic heavy-ion collisions *event-by-event*
- iEBE-JET interface couples medium evolution with rare probes (EM, jet, heavy-quark) has been developed
- iEBE-JET has been applied to phenomenological studies to resolve direct photon flow puzzle

Coming soon

- Bulk viscosity, conserved current (net baryon density), pre-equilibrium dynamics

Thank you!


HDFView 2.9
File Window Tools Help
Recent Files
/Users/Chun/Desktop/VISHJet/JetReader_h5/JetData.h5
Clear Text
Event
Frame_0000
BulkPi
P
Pi00
Pi01
Pi02
Pi03
Pi11
Pi12
Pi13
Pi22
Pi23
Pi33
Temp
Vx
Vy
e
s
Frame_0001
Frame_0002
Frame_0003
Frame_0004
TableView - e - /Event/Frame_0000/ - /Users/Chun/Desktop/VISHJet/JetR...
Table
33, 35 =
33.47711998625081
30 31 32 33 34 35
15 9540... 5.501333... 4.243892... 3.012244... 1.940196... 1.102955... 0.537
16 4619... 11.24030... 9.015574... 6.739031... 4.616935... 2.864968... 1.558
17 2683... 19.32409... 16.15839... 12.71244... 9.244180... 6.134277... 3.637
18 5986... 28.95650... 25.12282... 20.67867... 15.88110... 11.21342... 7.137
19 2974... 38.77295... 34.77121... 29.77654... 24.02537... 17.91760... 12.15
20 0632... 47.78939... 43.83183... 38.76121... 32.61357... 25.62611... 18.40
21 8827... 55.36830... 51.75123... 46.88671... 40.80240... 33.44054... 25.23
22 3627... 61.68726... 58.27822... 53.72573... 47.87399... 40.53977... 31.92
23 9032... 66.79653... 63.59296... 59.28769... 53.63173... 46.51820... 37.83
24 2114... 70.56792... 67.50041... 63.49622... 58.07359... 51.17967... 42.59
25 9398... 73.22076... 70.27761... 66.36614... 61.25957... 54.54567... 46.05
26 0716... 74.85708... 71.91222... 68.06815... 63.04095... 56.49256... 48.17
27 0525... 75.44244... 72.48026... 68.64248... 63.64327... 57.11430... 48.88
28 7326... 74.84248... 71.92227... 68.09761... 63.05448... 56.57156... 48.19
29 3280... 73.19948... 70.28023... 66.36931... 61.29588... 54.65882... 46.21
30 8418... 70.52506... 67.45372... 63.43256... 58.20686... 51.37563... 42.77
31 8113... 66.62568... 63.47792... 59.24158... 53.74454... 46.65683... 37.96
32 6087... 61.60145... 58.21612... 53.73818... 47.89930... 40.62639... 32.05
33 1221... 55.28014... 51.65916... 46.82691... 40.76745... 33.47711... 25.31
34 5250... 47.65685... 43.74935... 38.73913... 32.62259... 25.65196... 18.41
35 8195... 38.74274... 34.67429... 29.70844... 24.00035... 17.93292... 12.15
36 8004... 28.93837... 25.12687... 20.67658... 15.89817... 11.22946... 7.146



HDFView 2.9
File Window Tools Help
Recent Files
/Users/Chun/Desktop/VISHJet/JetReader_h5/JetData.h5
Clear Text
Event
Frame_0000
BulkPi
P
Pi00
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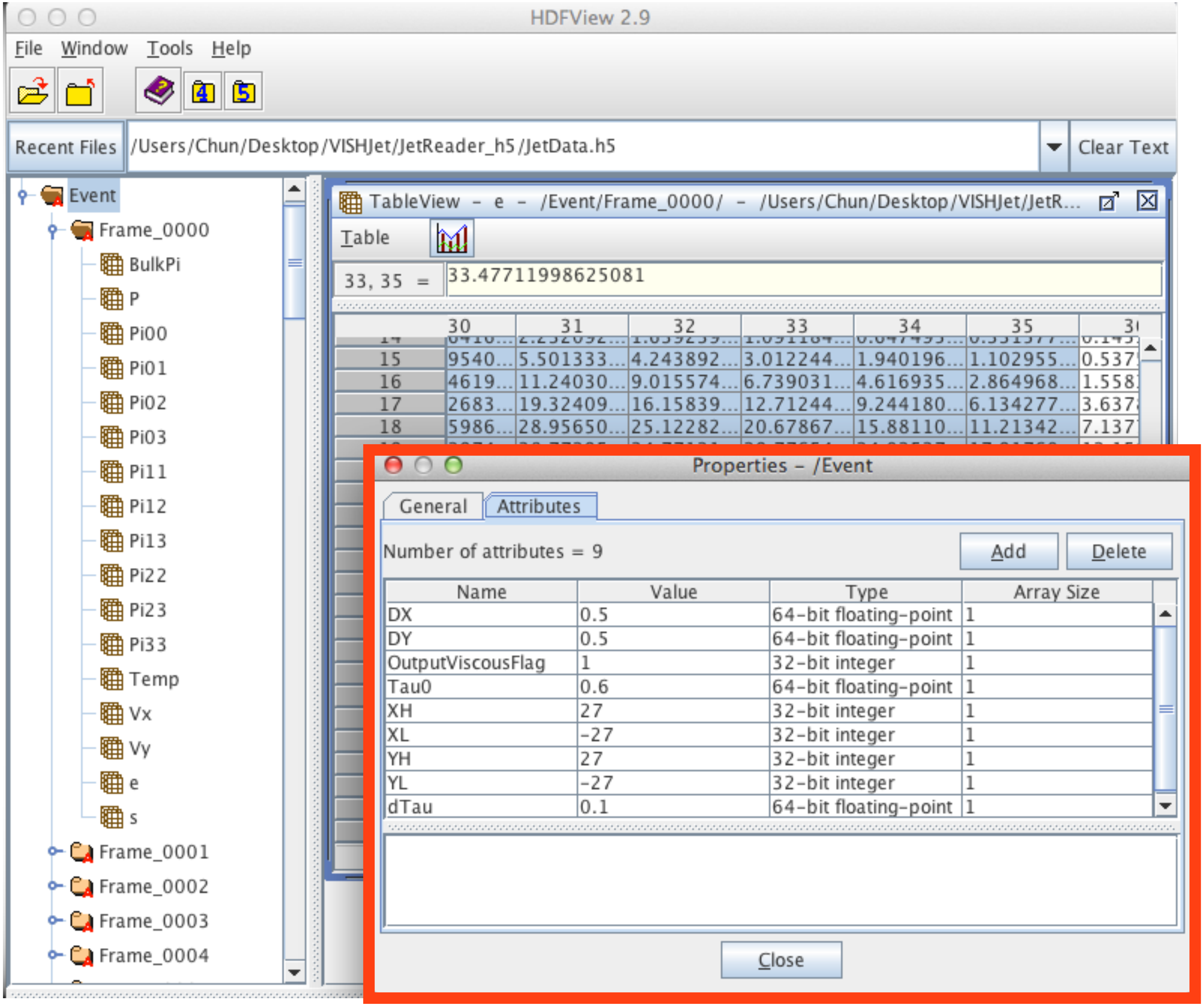
Pi03
Pi11
Pi12
Pi13
Pi22
Pi23
Pi33
Temp
Vx
Vy
e
s
Frame_0001
Frame_0002
Frame_0003
Frame_0004
TableView - e - /Event/Frame_0000/ - /Users/Chun/Desktop/VISHJet/JetR...
Table
33, 35 =
33.47711998625081
Lineplot - /Event/Frame_0000/e - by column
30
31
32
33
34
35
Close


HDFView 2.9
File
Window
Tools
Help
Recent Files
/Users/Chun/Desktop/VISHJet/JetReader_h5/JetData.h5
Clear Text
Event
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BulkPi
P
Pi00
Pi01
Pi02
Pi03
Pi11
Pi12
Pi13
Pi22
Pi23
Pi33
Temp
Vx
Vy
e
s
Frame_0001
Frame_0002
Frame_0003
Frame_0004
TableView - e - /Event/Frame_0000/ - /Users/Chun/Desktop/VISHJet/JetR...
Table
33, 35 =
33.47711998625081
Properties - /Event
General
Attributes
Number of attributes = 9
Add
Delete
Name
Value
Type
Array Size
DX 0.5 64-bit floating-point 1
DY 0.5 64-bit floating-point 1
OutputViscousFlag 1 32-bit integer 1
Tau0 0.6 64-bit floating-point 1
XH 27 32-bit integer 1
XL -27 32-bit integer 1
YH 27 32-bit integer 1
YL -27 32-bit integer 1
dTau 0.1 64-bit floating-point 1
Close