Electromagnetic Probes as Multi-Messengers

Sebastian Scheid
Goethe University Frankfurt
EMMI Symposium, 1st August 2022

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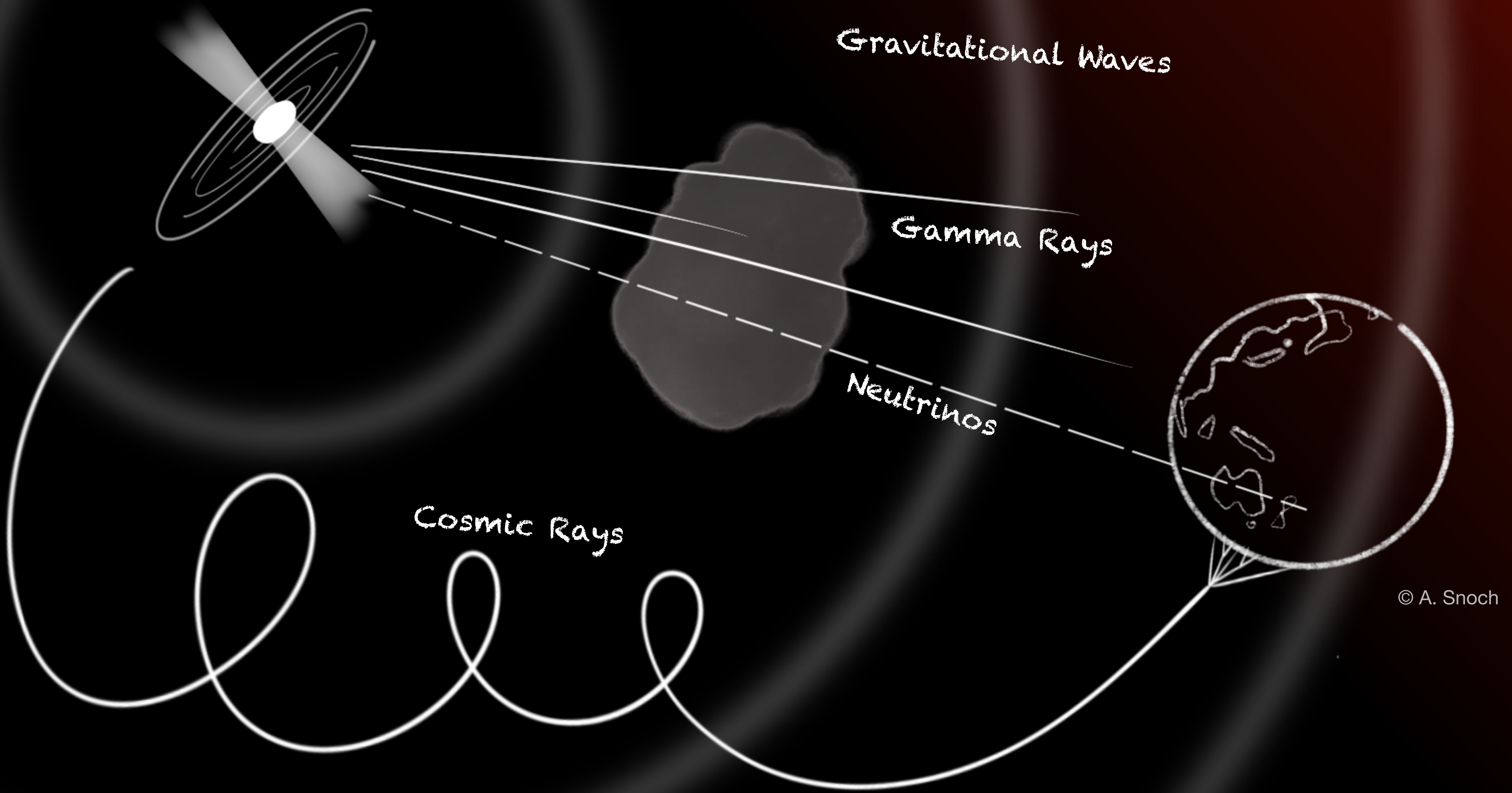
Multi Messengers



Electromagnetic Probes as Multi-Messengers of Heavy Ion Collisions

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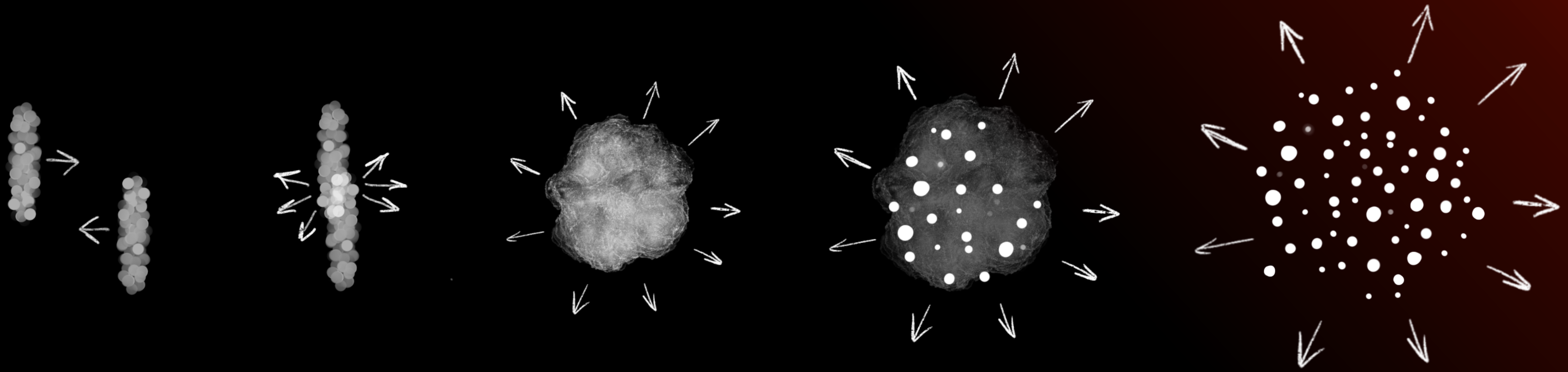
Act I	• Introduction
Act II	• A selection of (recent) results
Act III	• Perspectives for the future

The little big bang



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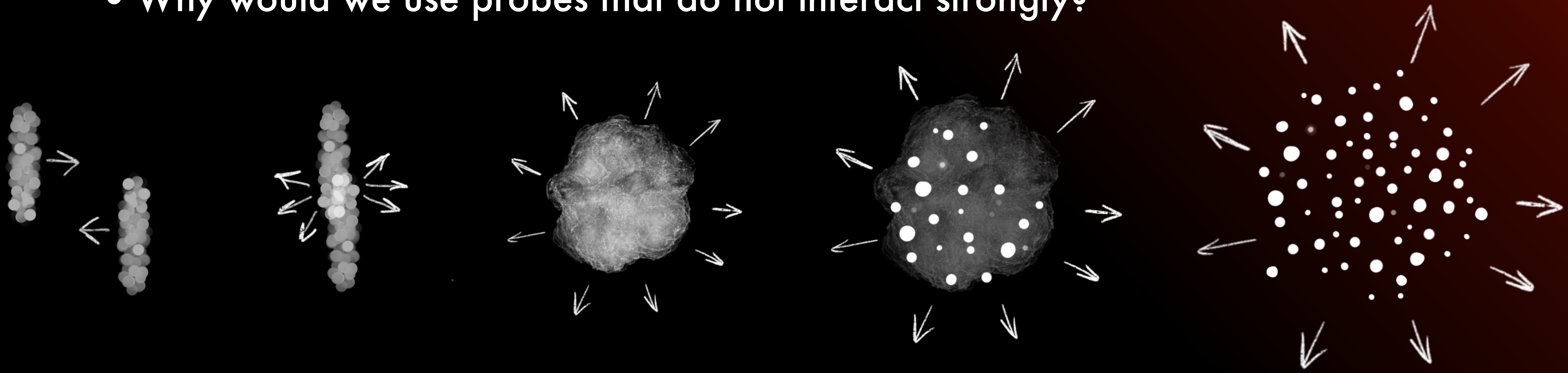
Why EM probes

We want to measure the properties of strongly interacting matter

- Why would we use probes that do not interact strongly?



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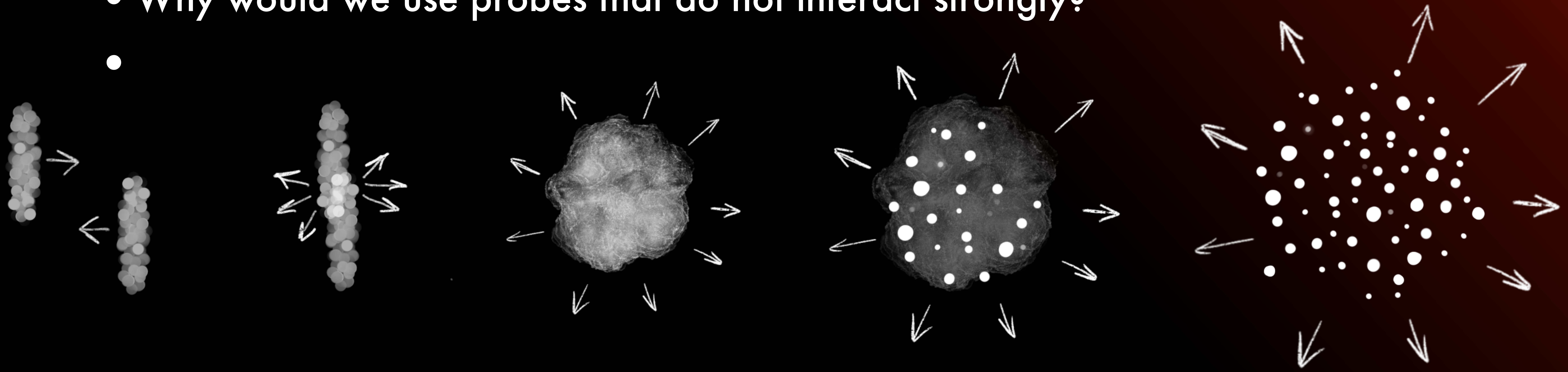

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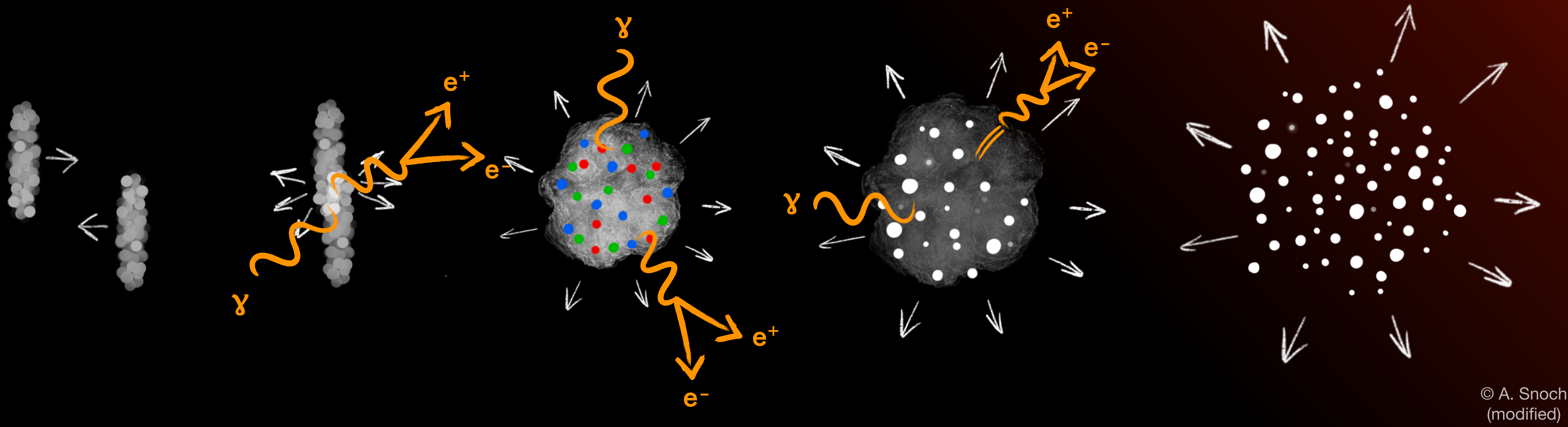
Hadronic probes have limited sensitivity to early stages of the collision

Why EM probes



Pre-equilibrium **Quark-gluon plasma** **Hadron Gas**

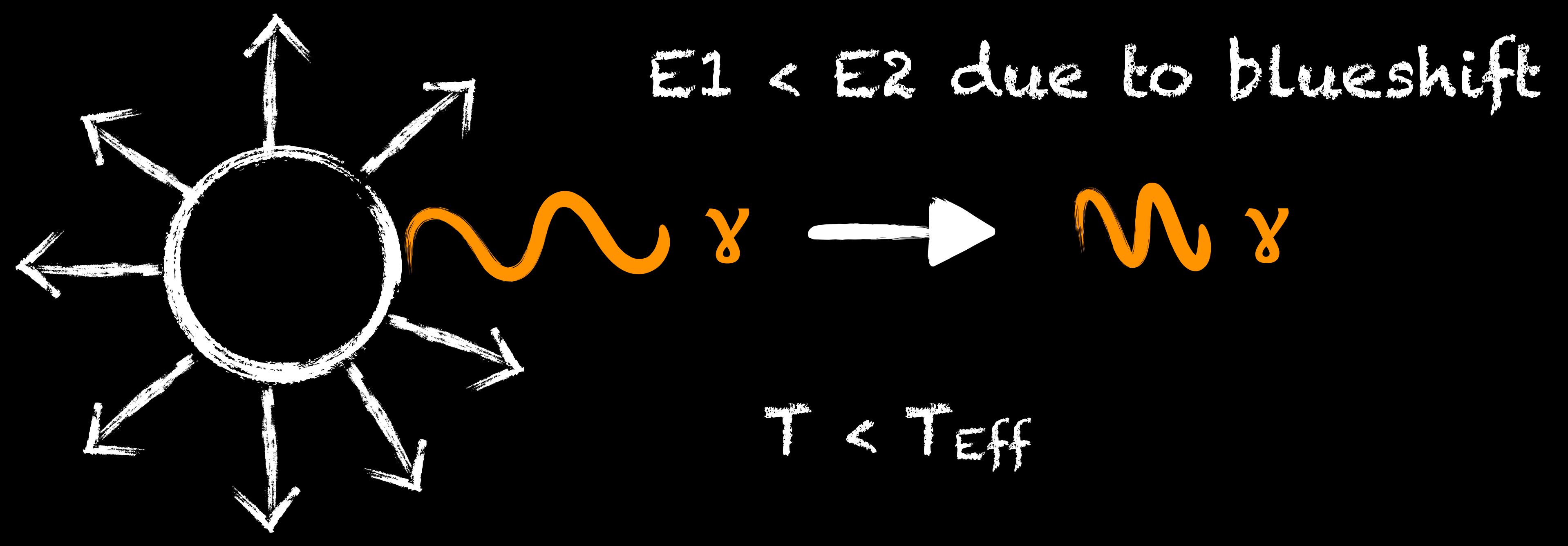
The Sources - Real direct Photons

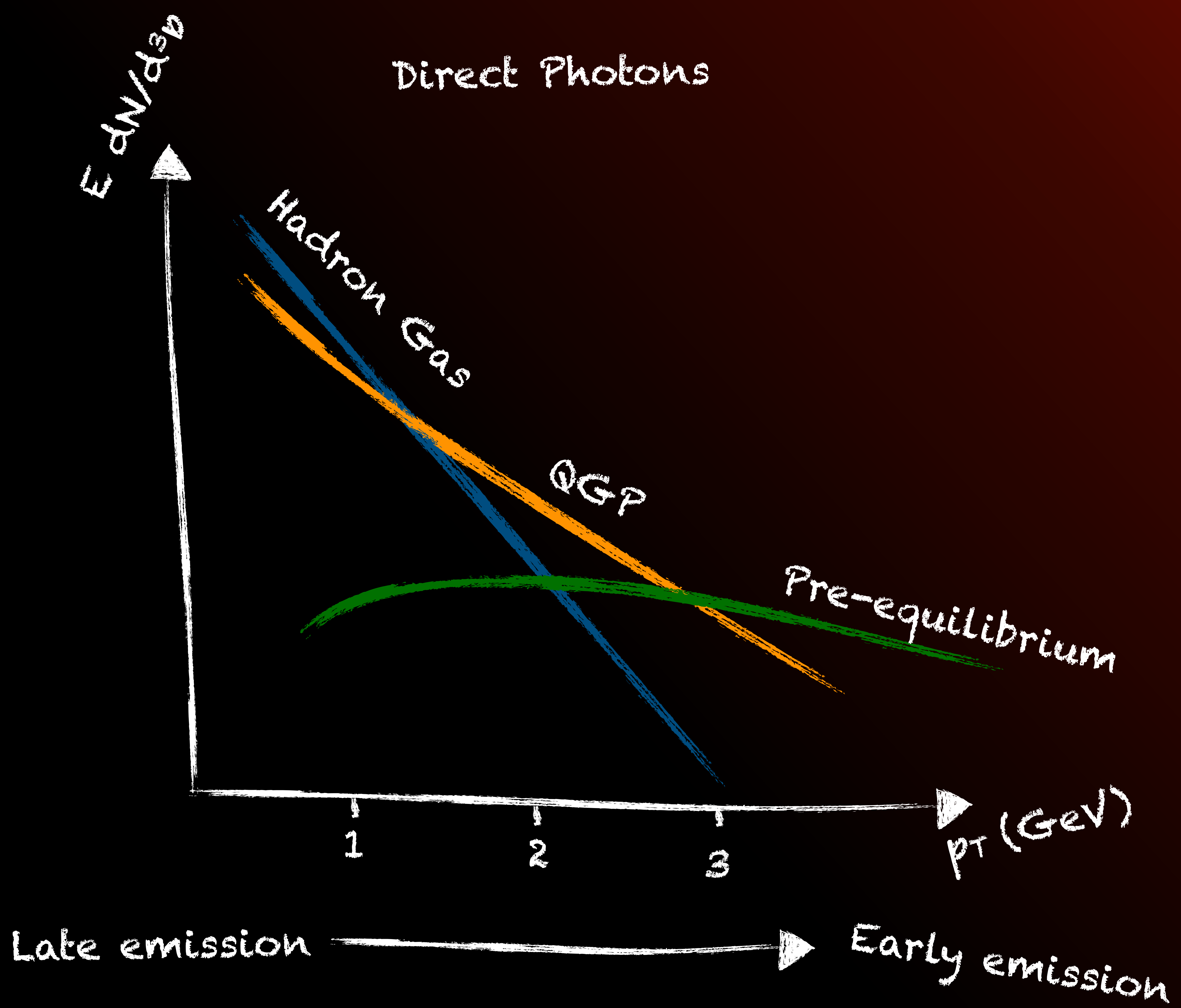
The different sources of EM radiation

- Thermal (QGP, Hadron gas)
- Hard scattering and pre-equilibrium

Inverse slope of thermal spectrum ∝ T of source

Sources populate different p_T ranges





The Sources - Dielectrons

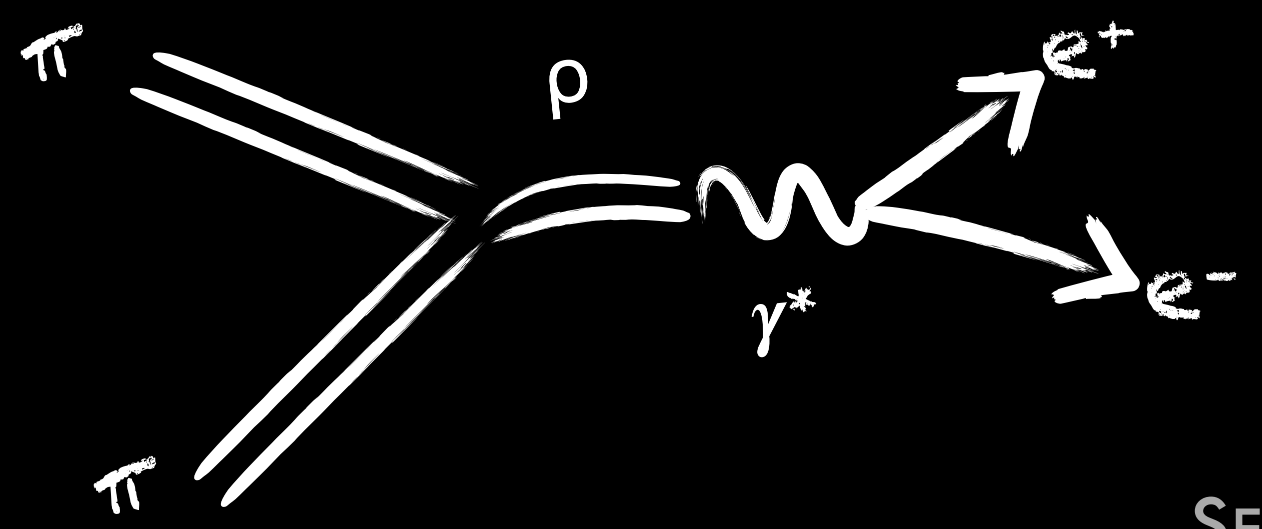
The different sources of EM radiation

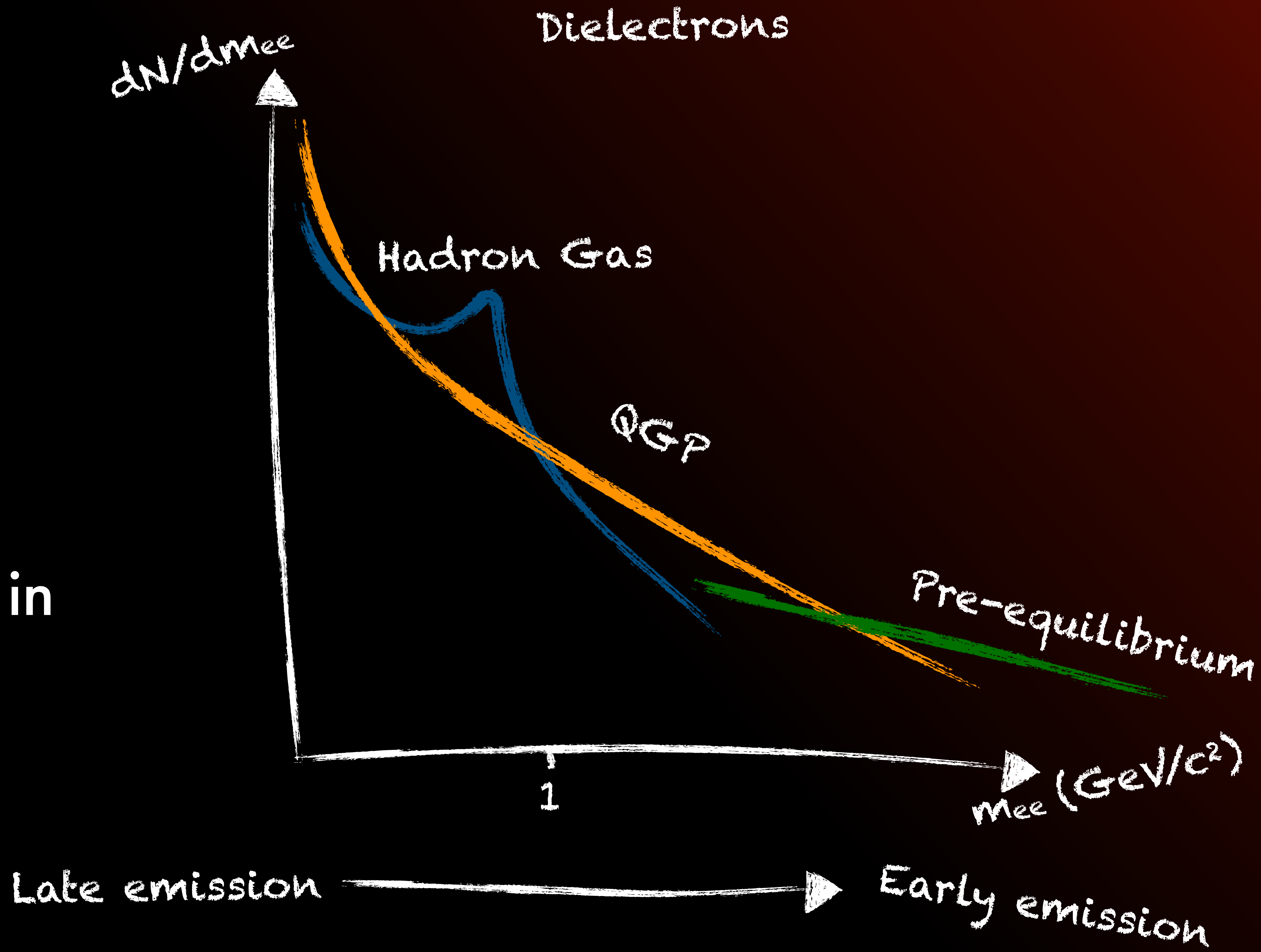
- Thermal (QGP, Hadron gas)
- Hard scattering and pre-equilibrium

Inverse slope of thermal spectrum ∝ T of source

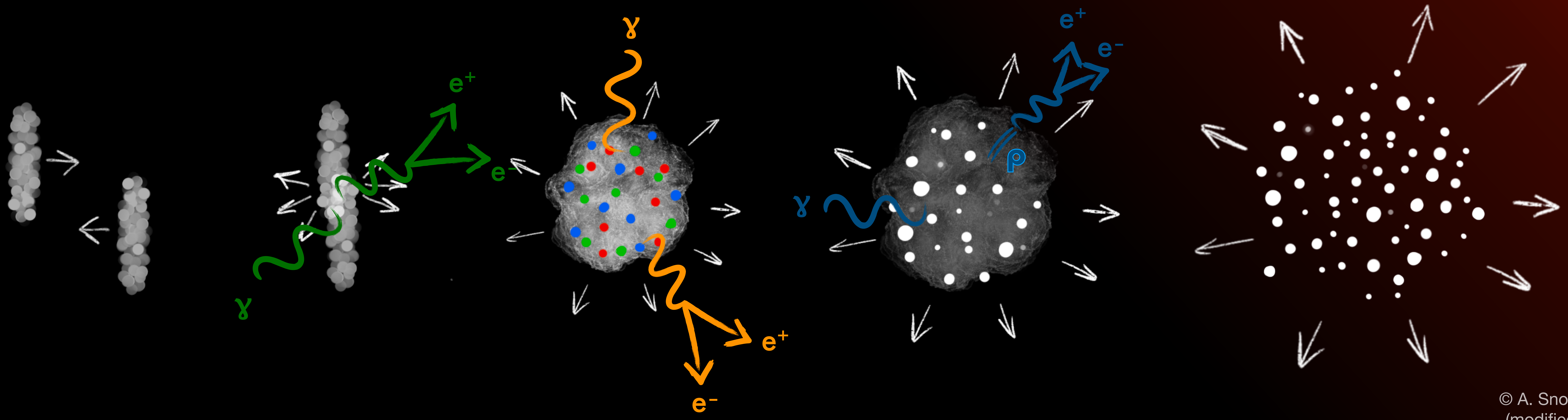
Sources populate different mass ranges

- Invariant mass unaffected by blueshift
- Structure in hadron gas → sensitivity to in medium spectral function of ρ



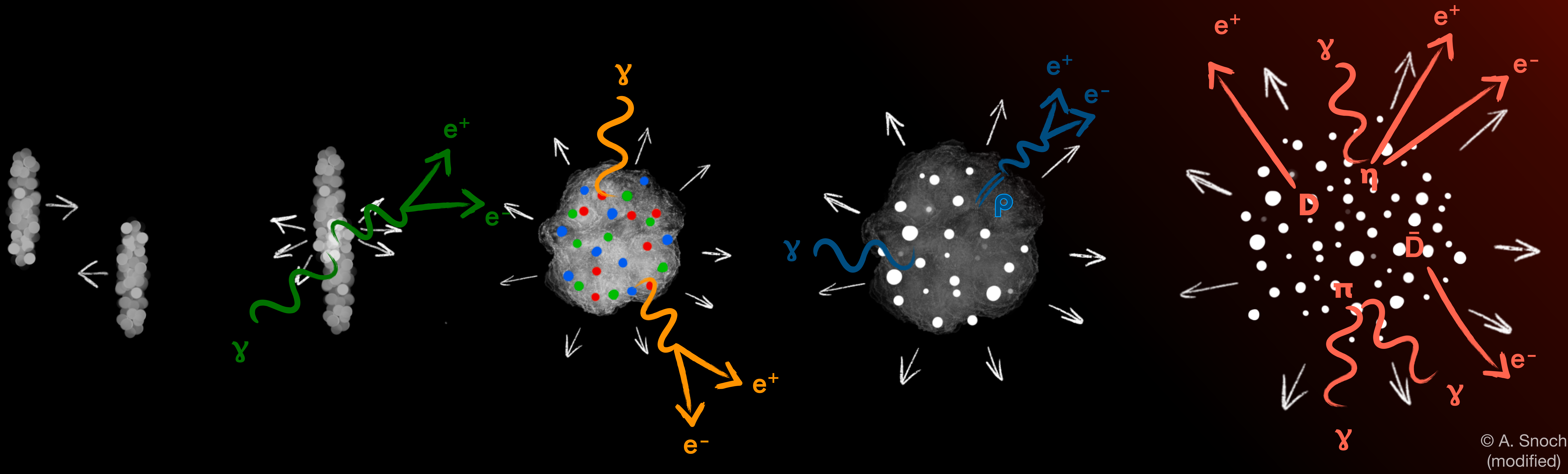


The Sources



Pre-equilibrium **Quark-gluon plasma** **Hadron Gas**

The Sources and background



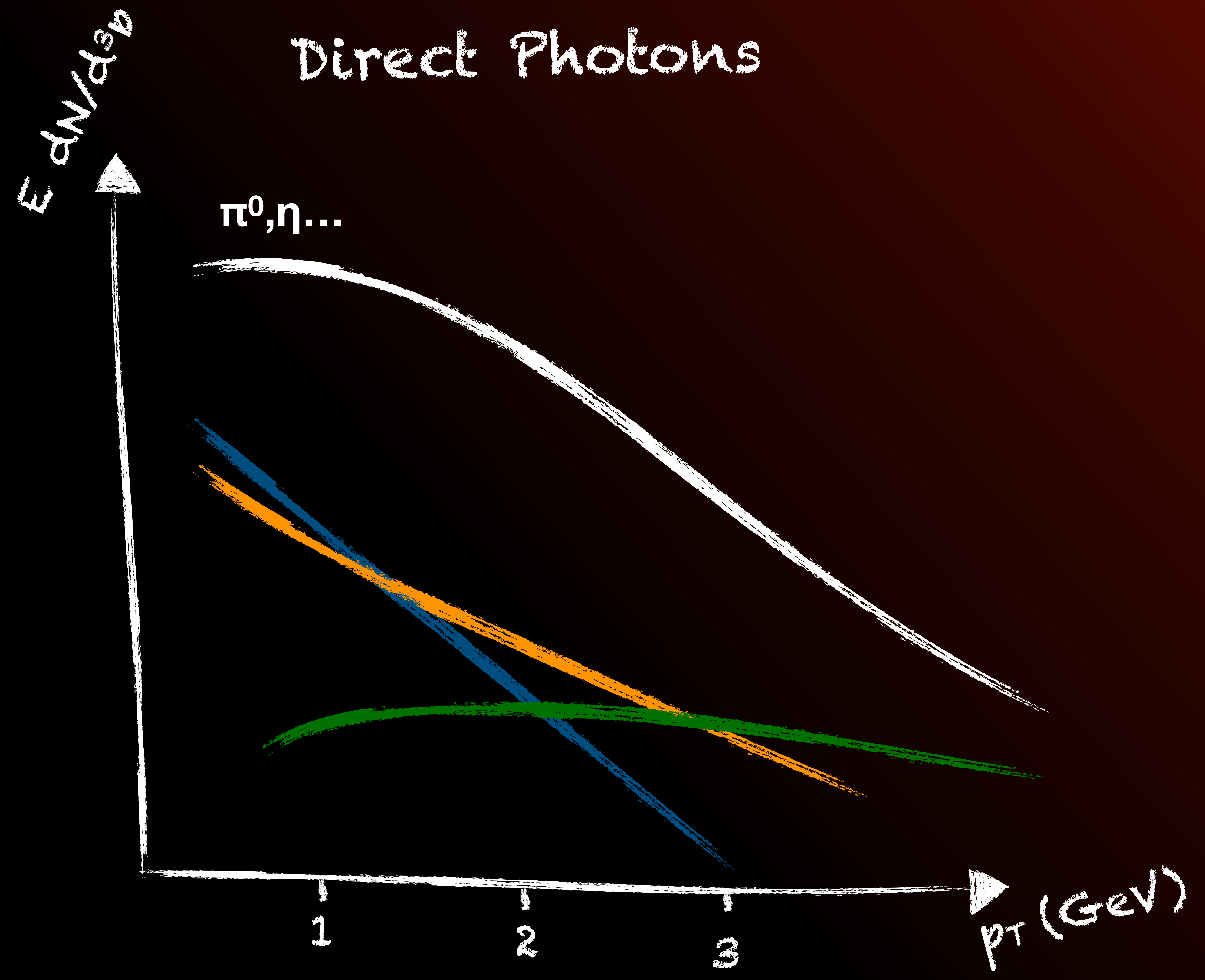
Pre-equilibrium | Quark-gluon plasma | Hadron Gas | Late stage hadron decays

The Backgrounds

- Dileptons: Combinatorial background of “fake” pairs
- Irreducible physical backgrounds
  $\pi^0 \rightarrow \gamma\gamma$ or γe^+e^-, $\eta \rightarrow \gamma\gamma$ or γee
  $c\bar{c} \rightarrow D\bar{D} \rightarrow e^+ e^- X Y$ (semi leptonic decays)
- A precice understanding of the sources of these backgrounds is needed to model and subtract them
- In the case of open heavy flavour experimental techniques can be employed to reduce them (Use the finite decay length)

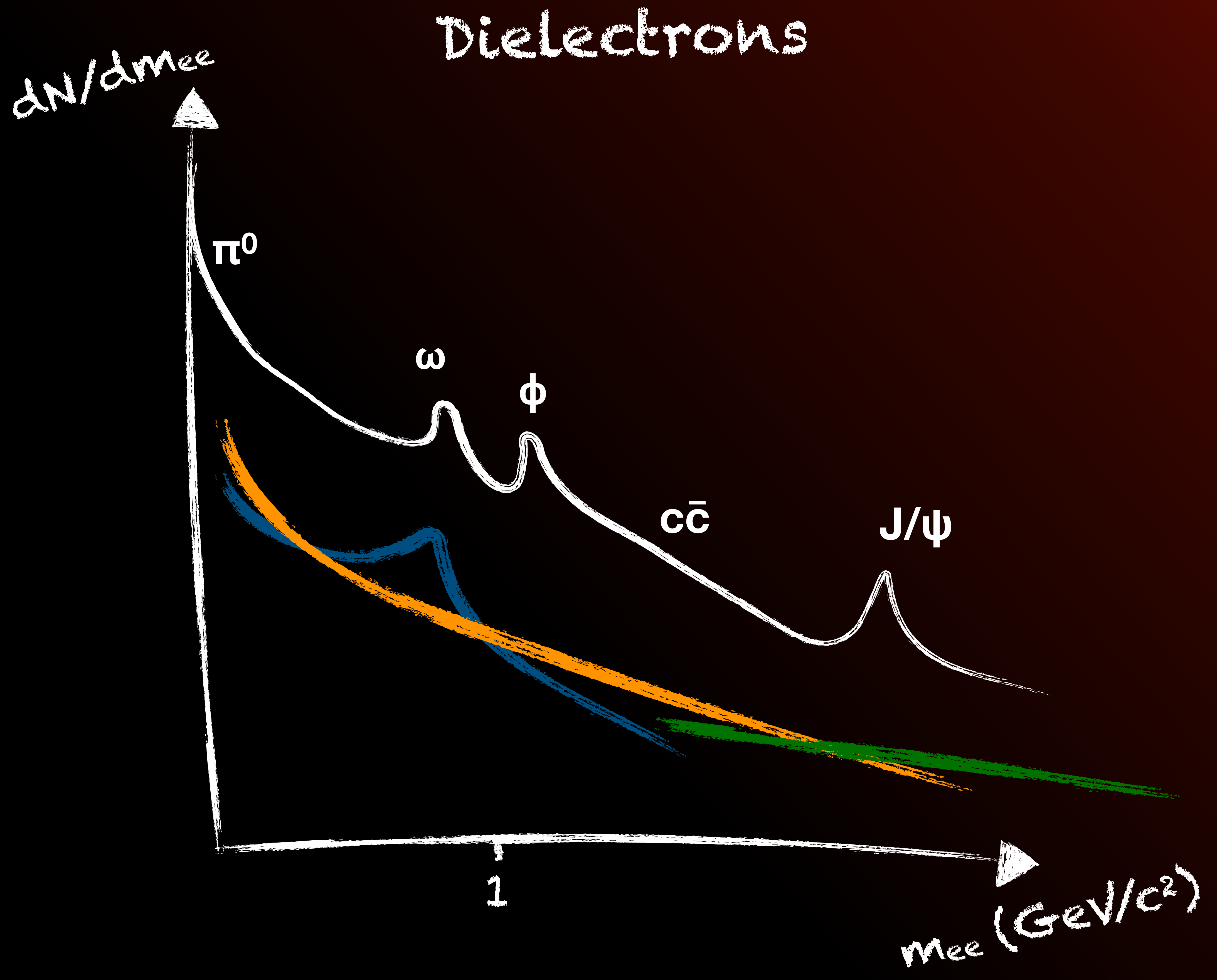
The hadronic Cocktail

- Best possible estimate of the estimate of contributions from hadronic decays
- Based on independent measurements
- Parameterised spectra used to model contribution in dielectron and photon spectra



The hadronic Cocktail

- Best possible estimate of the estimate of contributions from hadronic decays
- Based on independent measurements
- Parameterised spectra used to model contribution in dielectron and photon spectra
- Heavy flavour challenging to describe in heavy ion collisions (cold nuclear matter + energy loss)



Summary I

Electromagnetic probes are produced in all stages of heavy ion collisions and carry their information to the detectors undisturbed

Momentum and mass allow selection of different sources of EM radiation and production time in the collision

Dielectrons vs direct photons

- Additional dimension (invariant mass)
- No blueshift in T measurement
- Smaller statistical precision
- Additional backgrounds

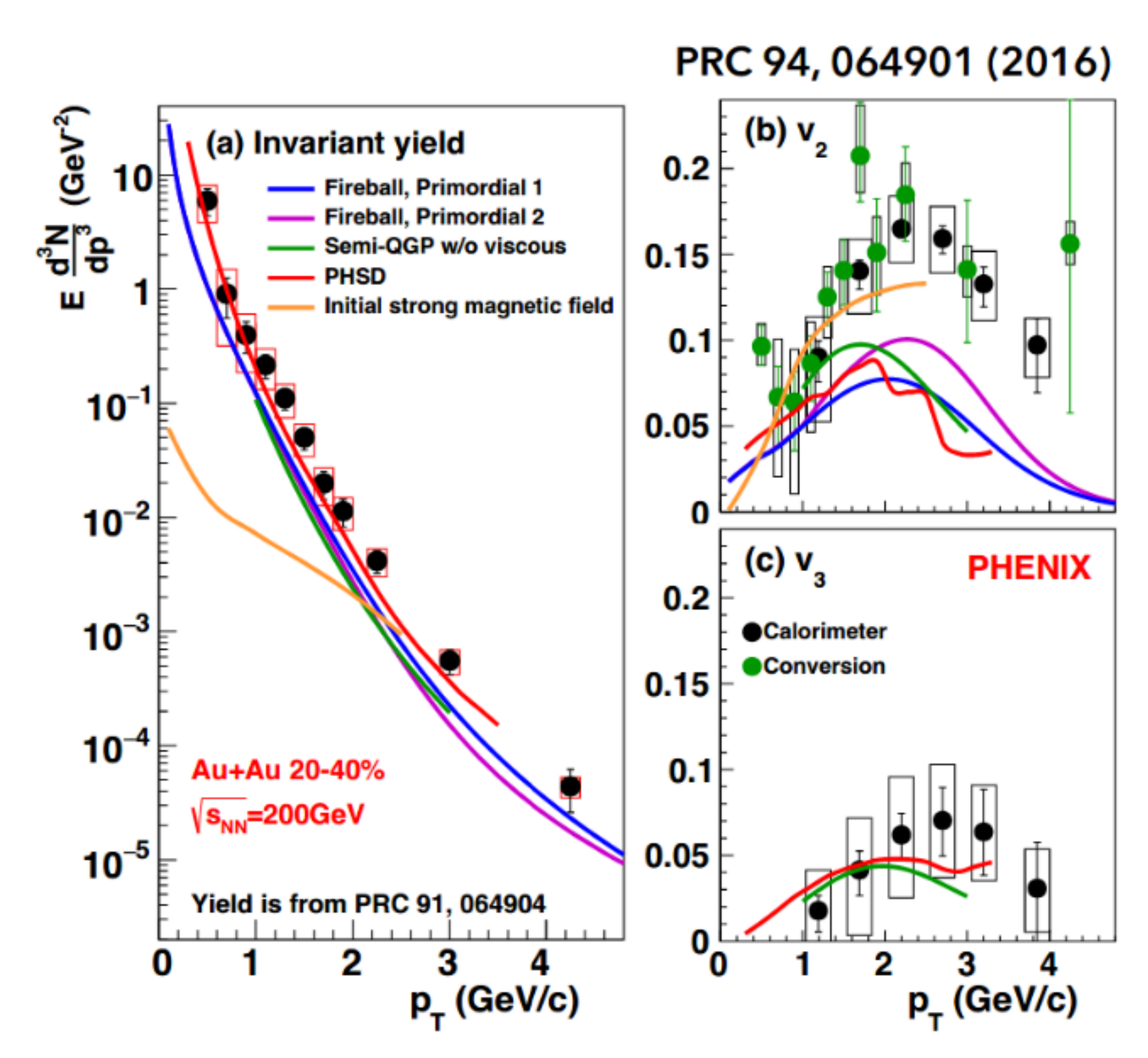
Where are we now?

The direct photon puzzle

Idea:

- Large yield →Early production due to high medium temperature (Partonic source)
- Large v_2 →Late emission since flow needs to build up (hadronic source)

Models are not able to describe yield and elliptic flow v_2 simultaneously



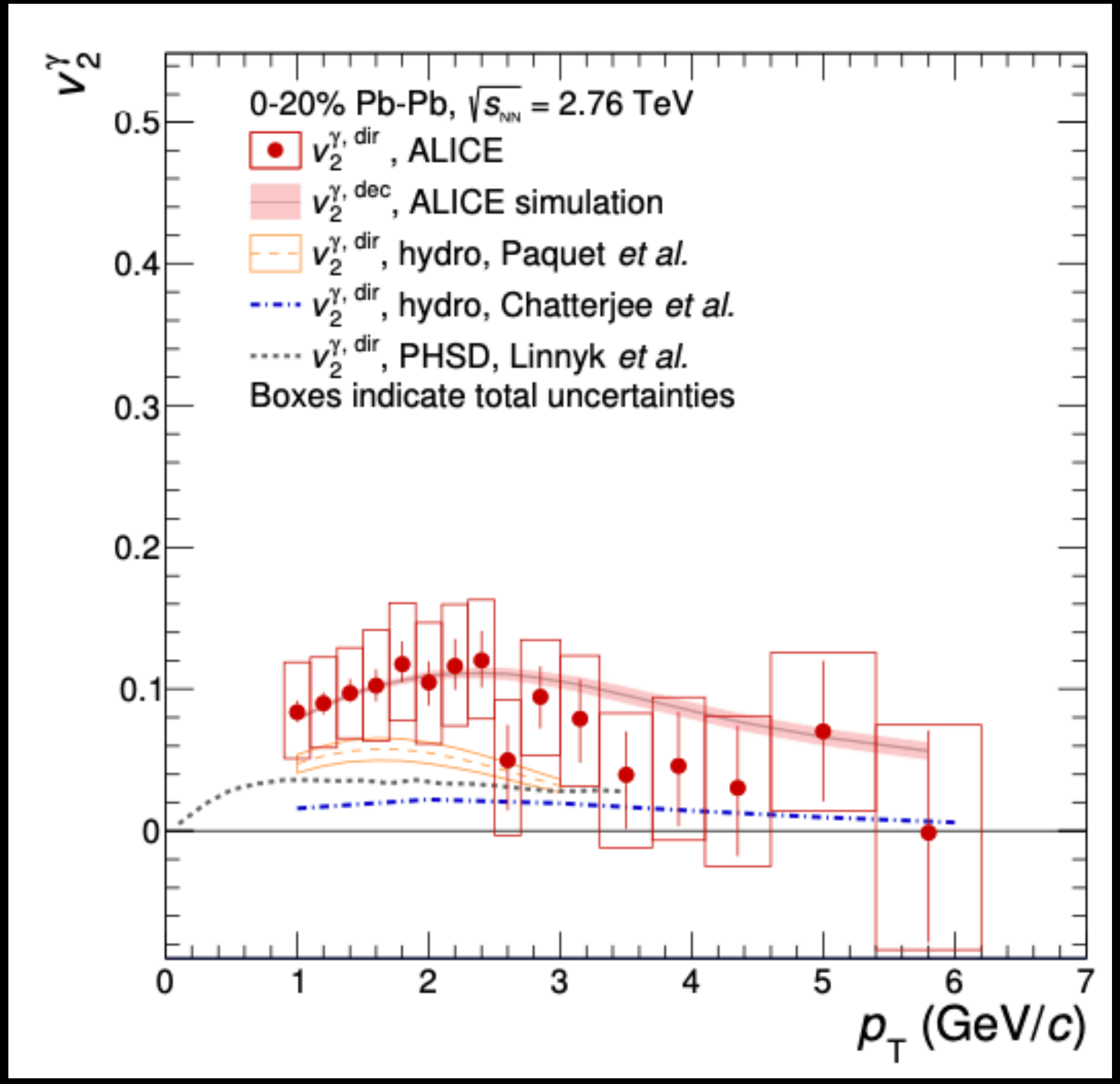
The direct photon puzzle

$v_{2,\gamma,dir}$ of direct photons at RHIC (PHENIX) and LHC (ALICE) ~$v_{2,\pi}$

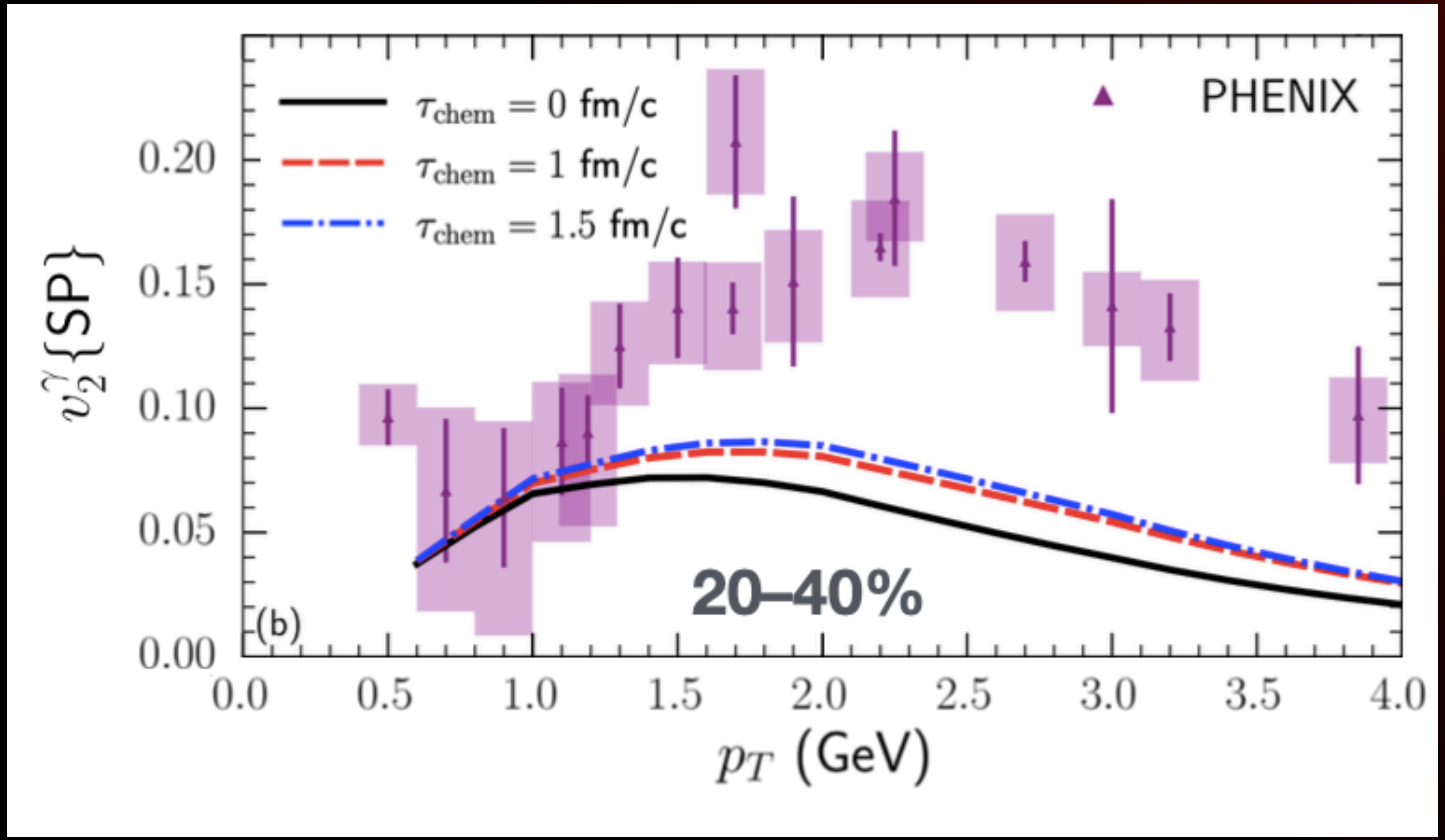
Photon production dominated by late stage?

Au–Au @ 200 GeV

ALICE, *Phys.Lett.B* 789 (2019) 308-322



Pb–Pb @ 2.76 TeV



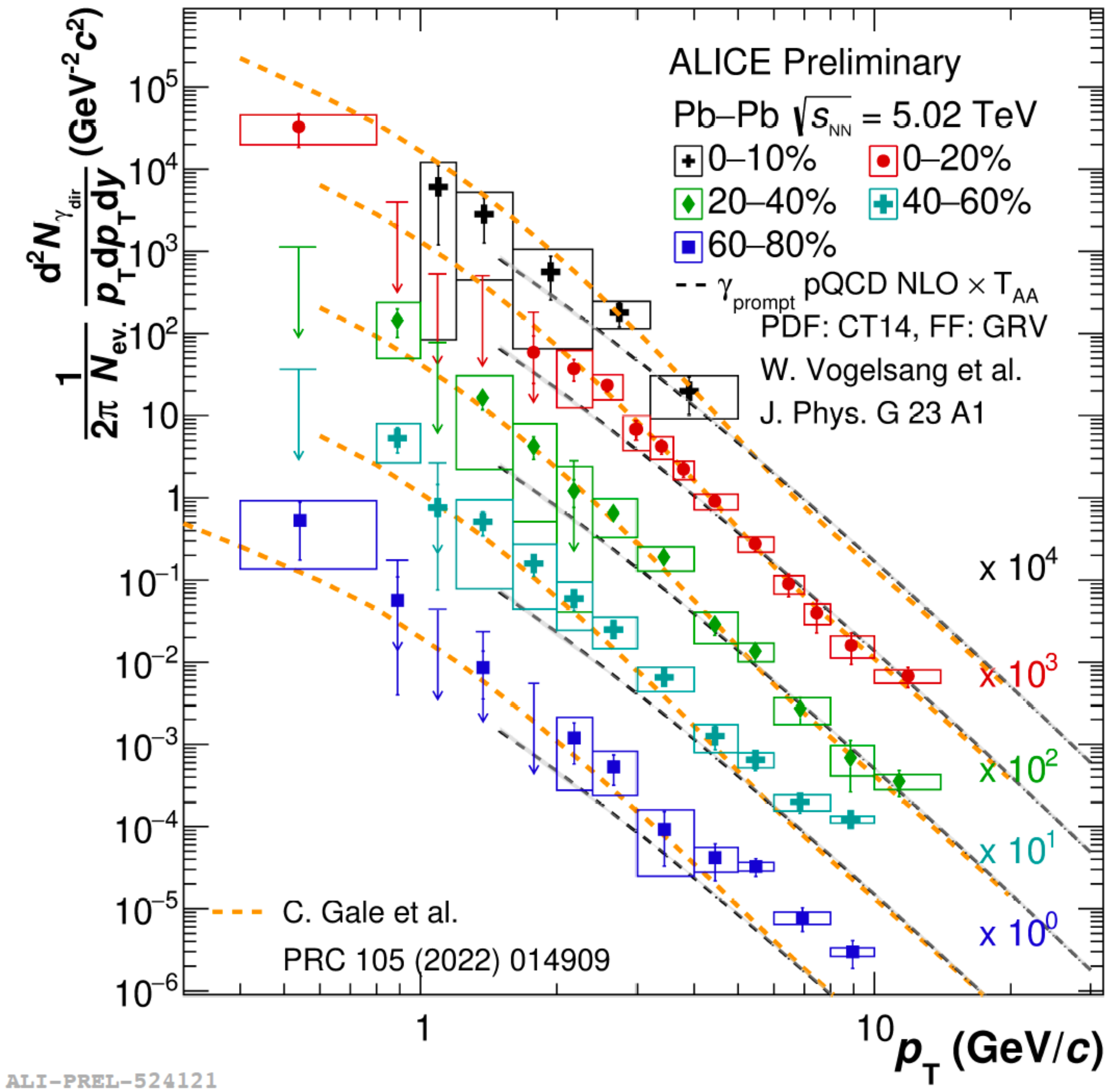
C. Gale et al., Phys.Rev.C 105 (2022) 1, 014909

Measurement of dielectron v_2 would be helpful

ALICE - Direct Photons

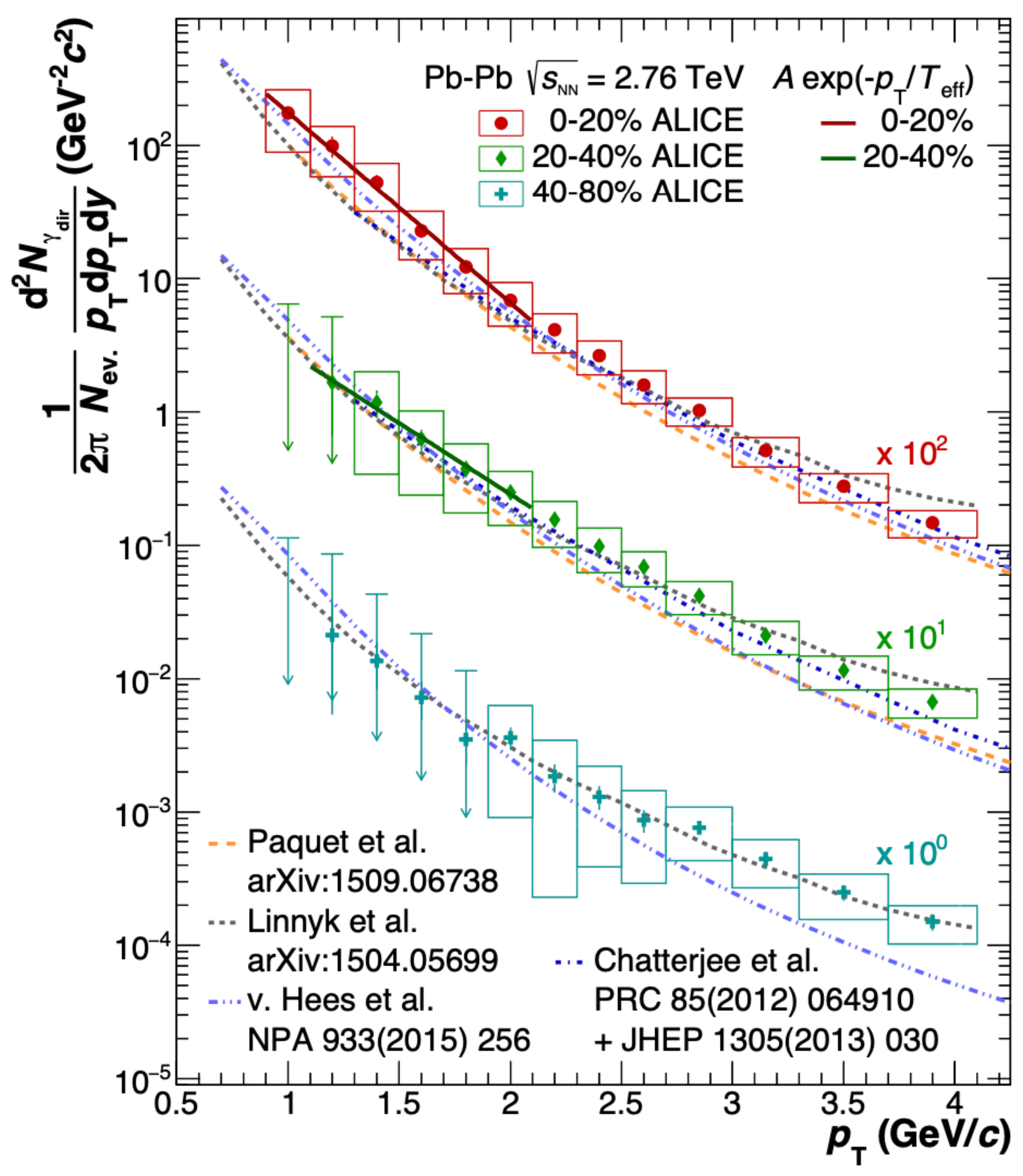
Data in agreement with models

T_{eff} results from 2.76 TeV:
0-20%: 297 ± 12 (stat) ± 41 (syst)



Pb–Pb @ 5.02 TeV

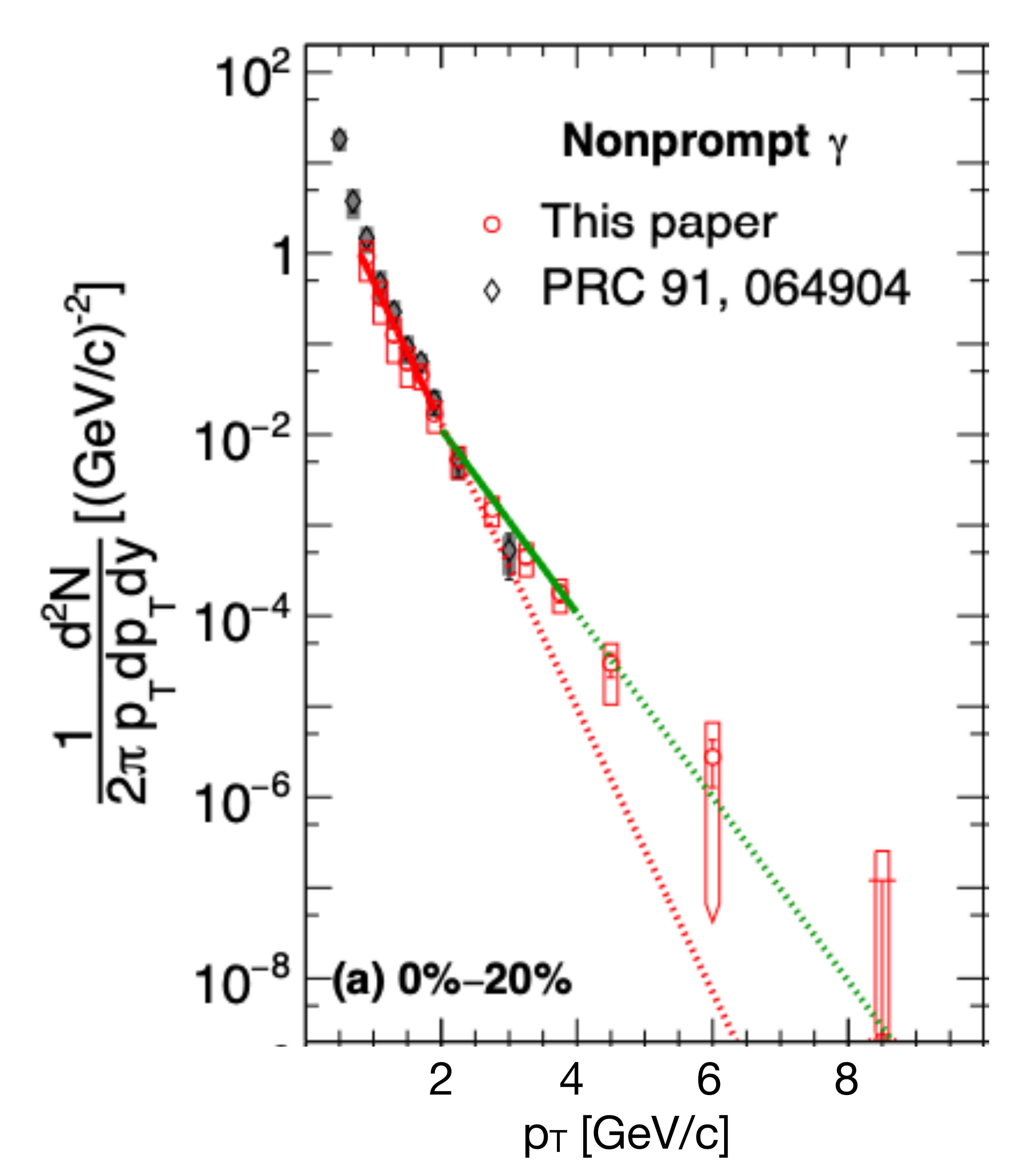
Pb–Pb @ 2.76 TeV



Phys. Lett. B 754 (2016) 235-248

PHENIX - Direct Photons

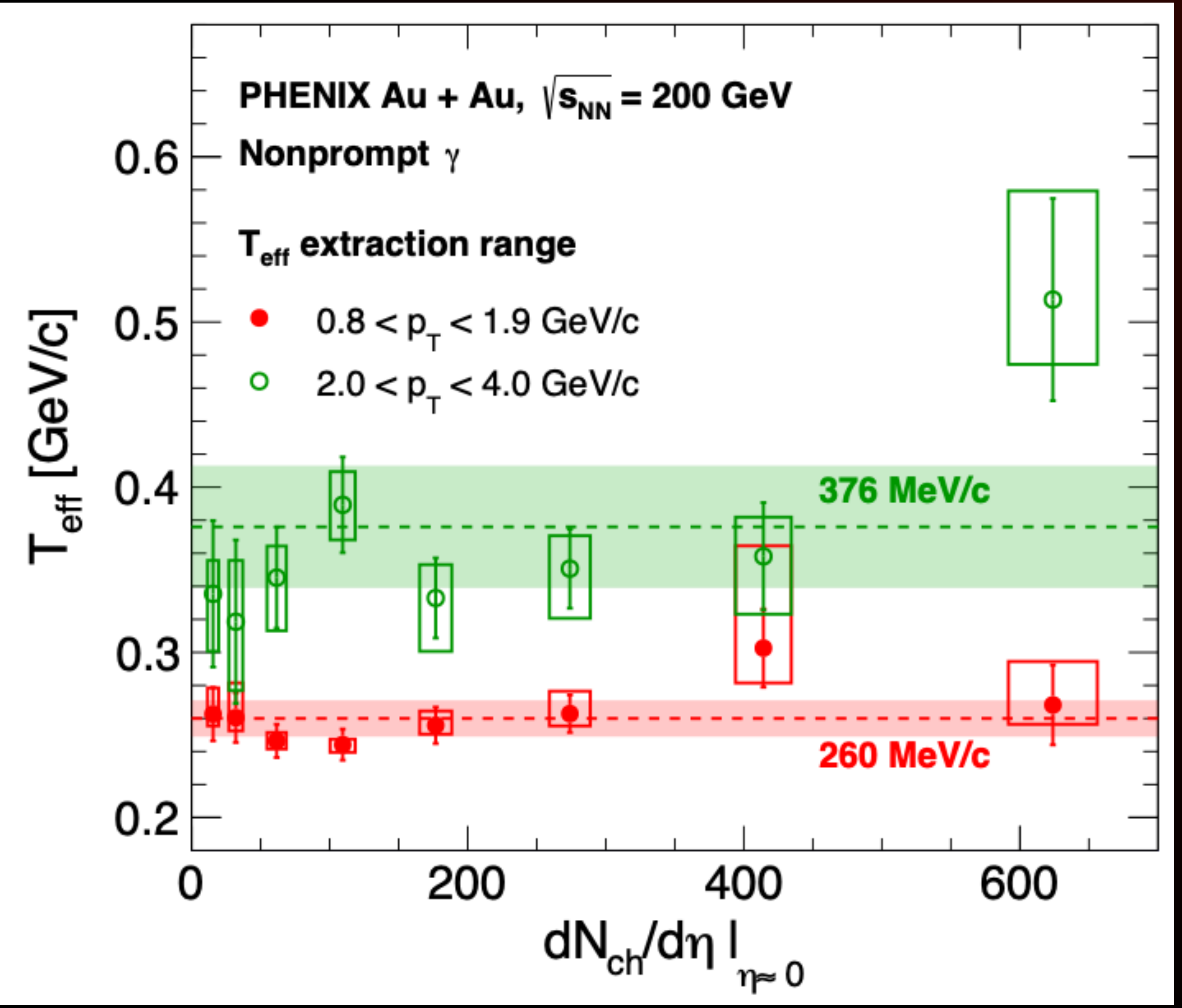
Au–Au @ 200 GeV



PHENIX, arXiv: 2203.17187

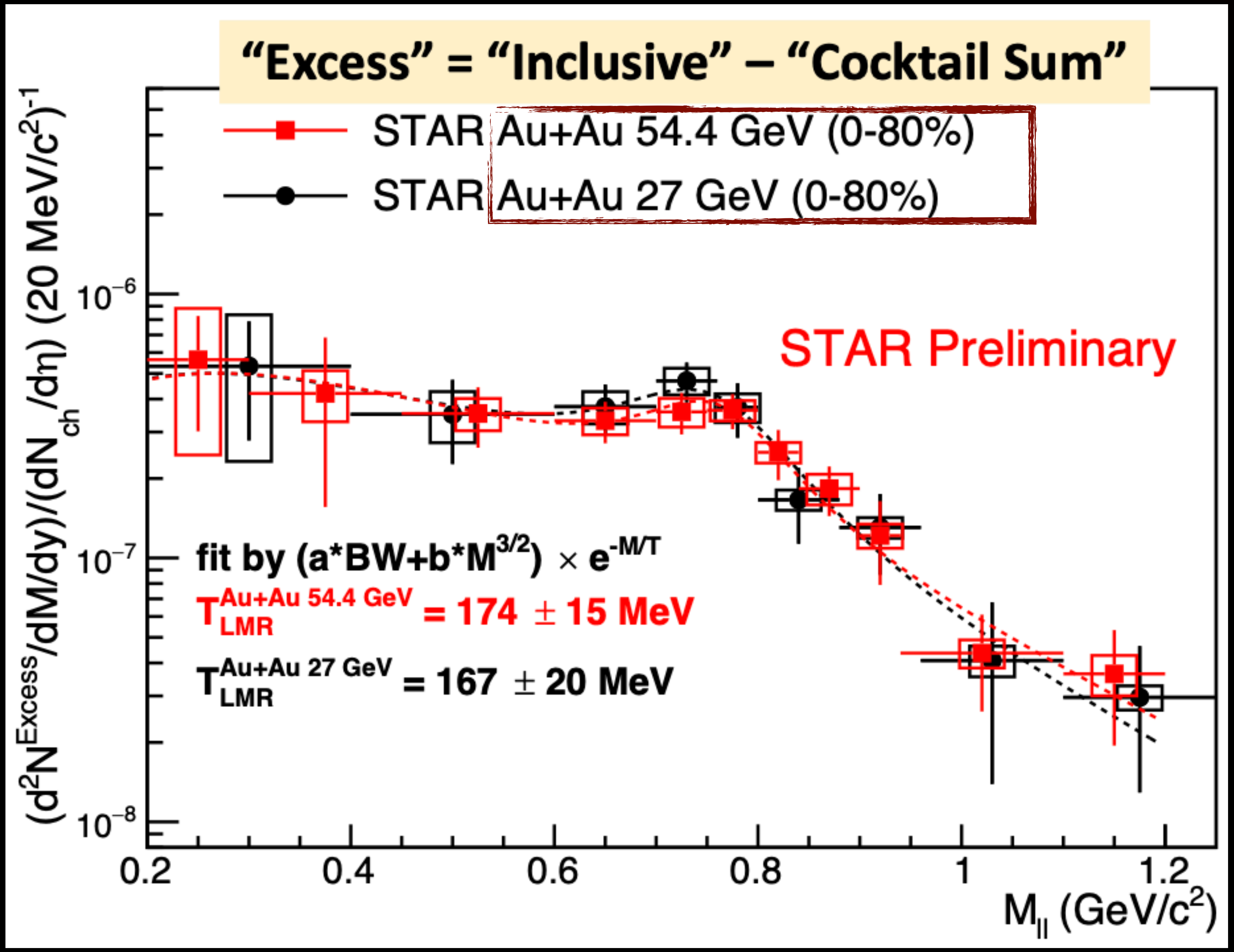
T_{eff} extracted from direct photon measurement in different p_T ranges

- Increases with p_T
- Earlier emission? Different source?



STAR - Dielectrons I

Zaochen Ye, QM2022



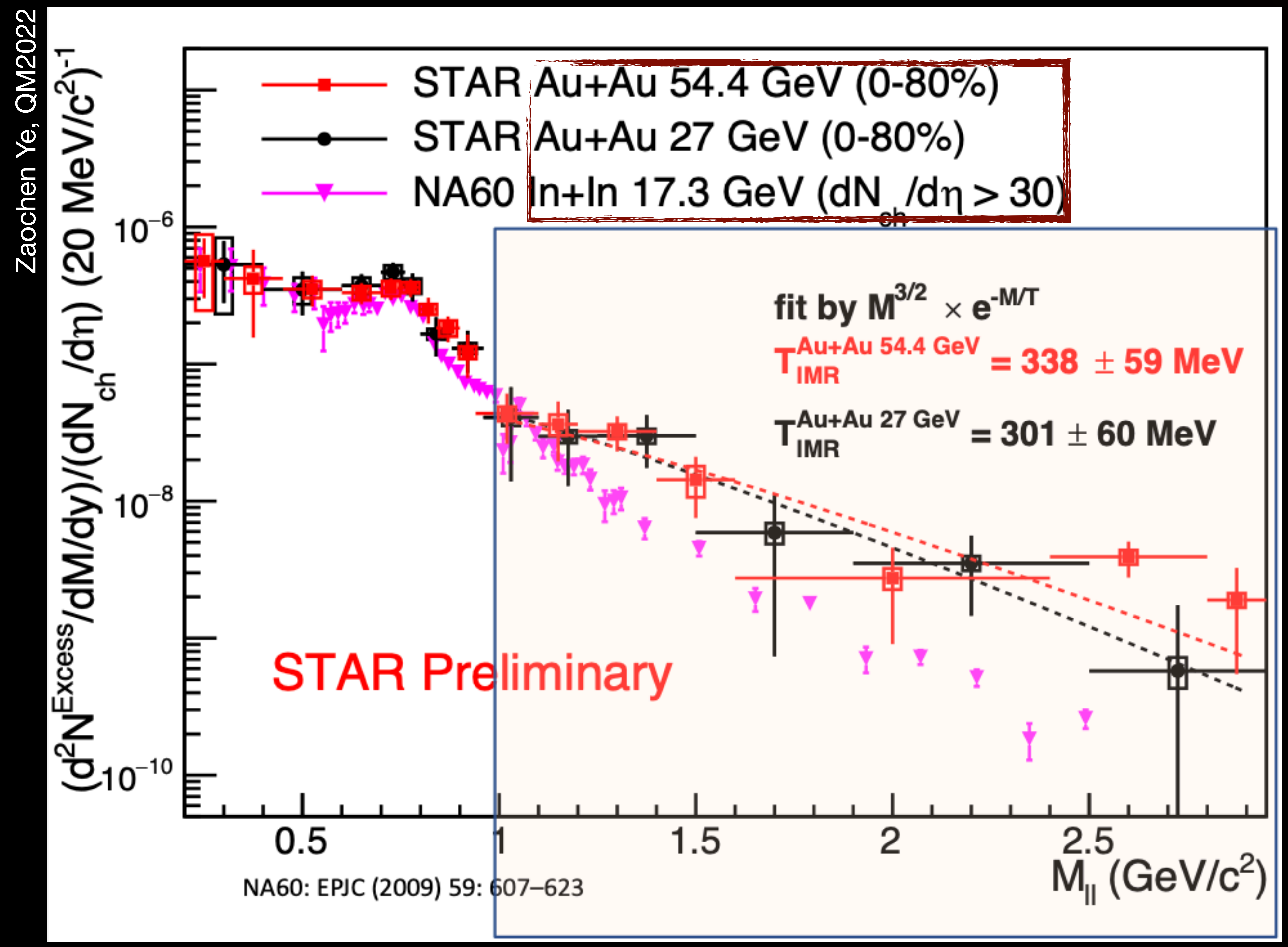
Late emission → Early emission

STAR sees clear enhancement wrt to hadronic cocktail

Fit of ρ Lineshape (Breit-Wigner) + thermal

Similar result with fit to NA60 In–In data at 17.3 GeV (165±4 MeV)

STAR - Dielectrons II



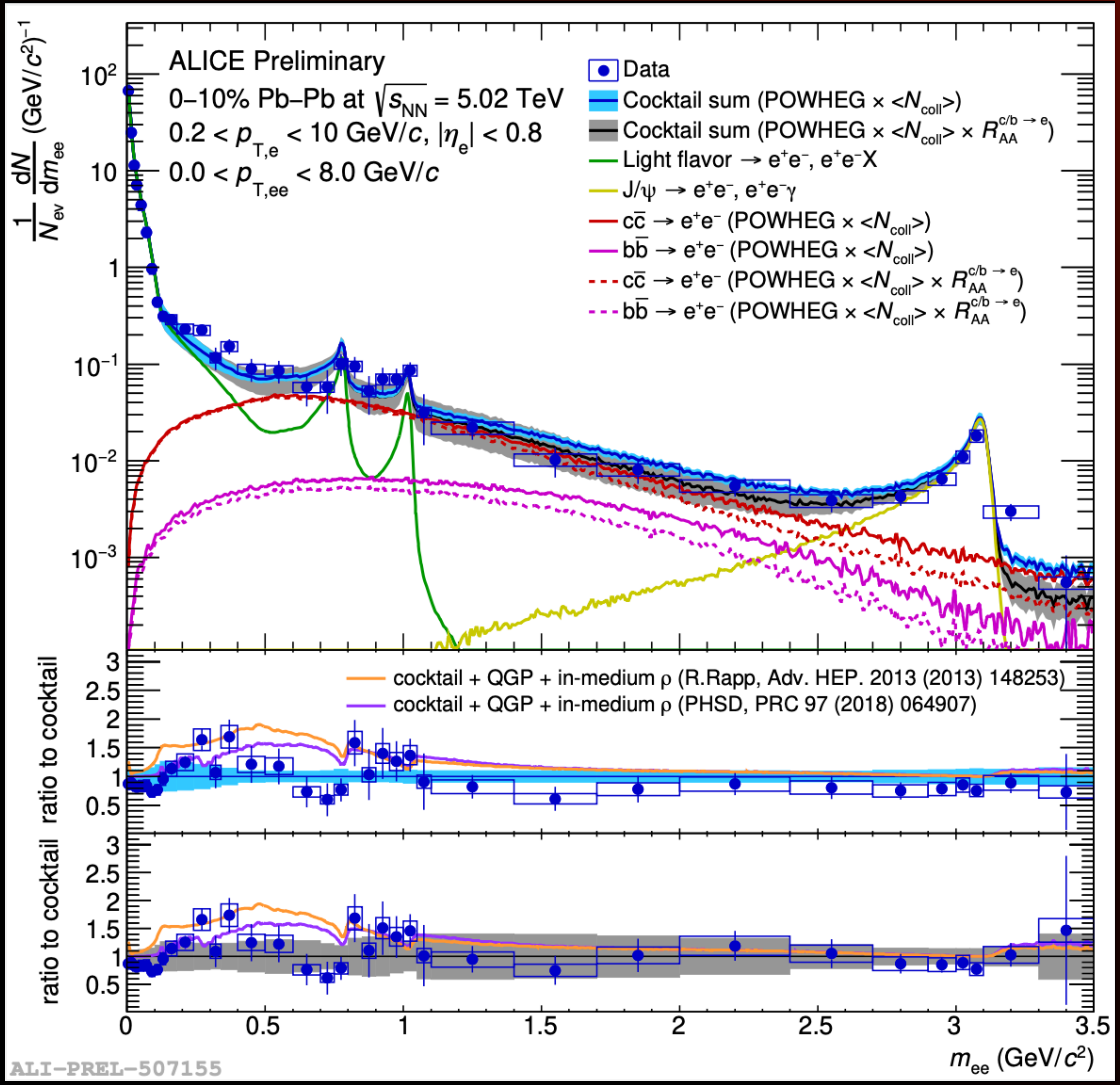
Late emission → Early emission

T extracted at higher mass significantly higher

NA60 = 205 ± 15 MeV

ALICE - Dielectrons

Pb–Pb @ 5.02 TeV



Comparison of dielectron spectrum with hadronic cocktail

HF cross section much higher than at RHIC

Two different approaches for HF

- N_{coll} scaled from pp measurement
- Additional R_{AA} of c/b→e

Handeling HF contribution crucial

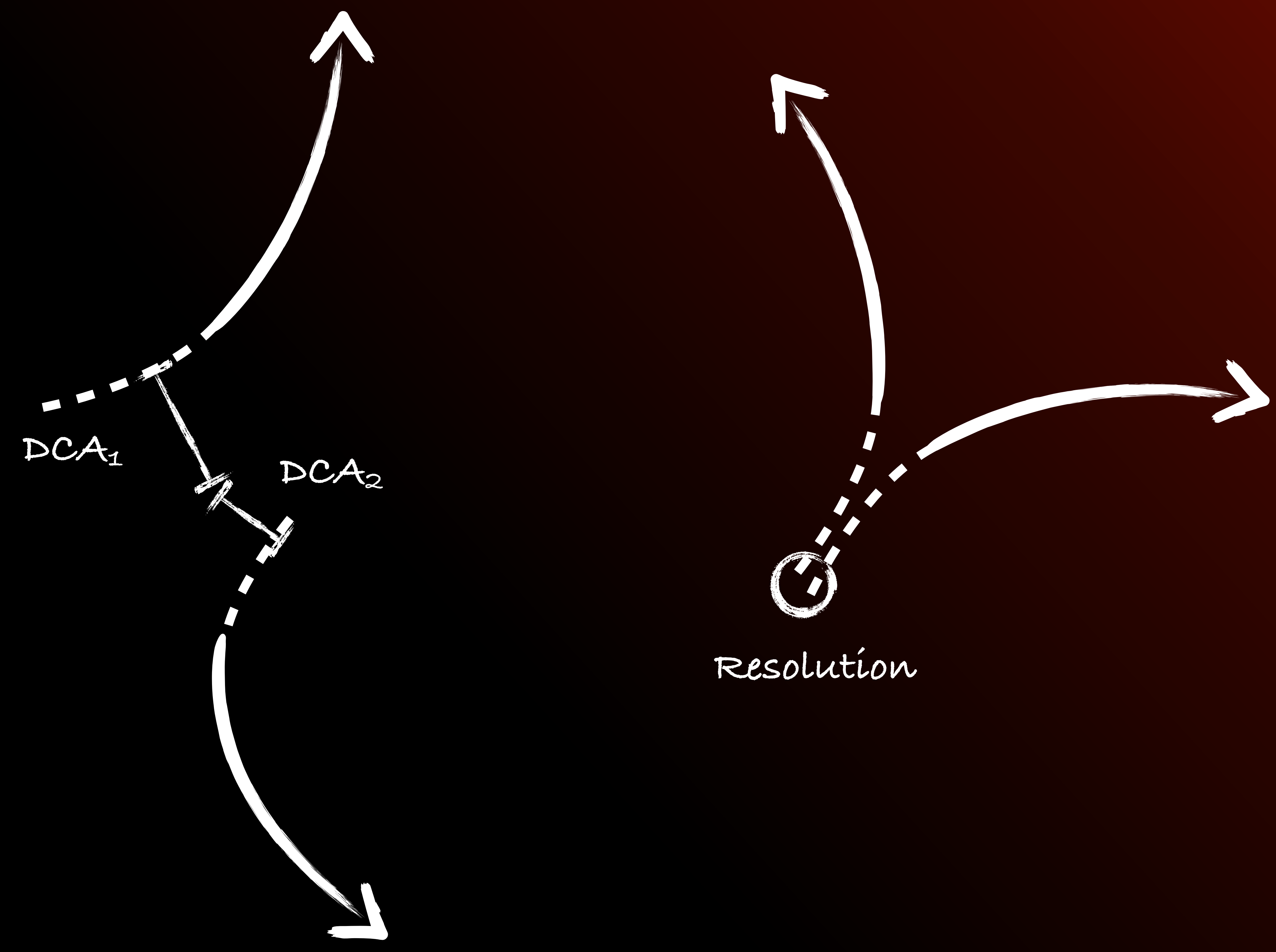
Distance of Closest Approach (DCA)

Heavy flavour hadrons have a finite decay length (150 - 500 µm)

$$\mathrm{DCA_{ee}} = \sqrt{\frac{\mathrm{DCA}_1^2 + \mathrm{DCA}_2^2}{2}}$$

with $\mathrm{DCA}_{1/2}$ normalised to respective resolution

First steps in pp in Pb−Pb collisions by ALICE



Summary II

Possibility to extract temperature in different mass and momentum regions at RHIC energies

- Higher mass/p_T yields in all cases higher temperature
- Can be attributed to earlier emission and possibly pre-equilibrium sources
- High temperature in IMR (300 MeV) by STAR could be due pre-equilibrium

Measurements at LHC challenging

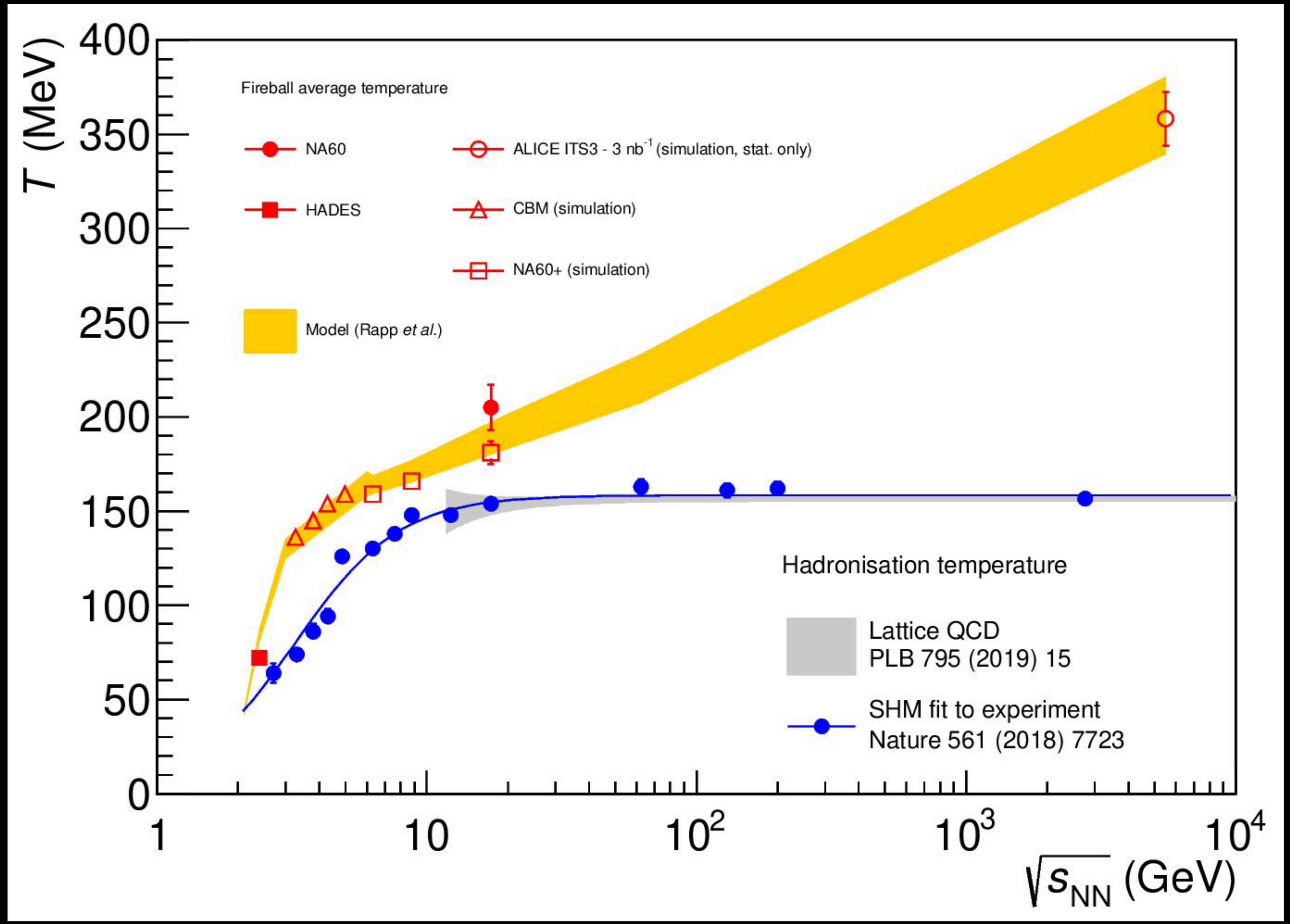
- Small signal to background ratio
- Large heavy-flavour background (dielectrons)

What is in the near future?

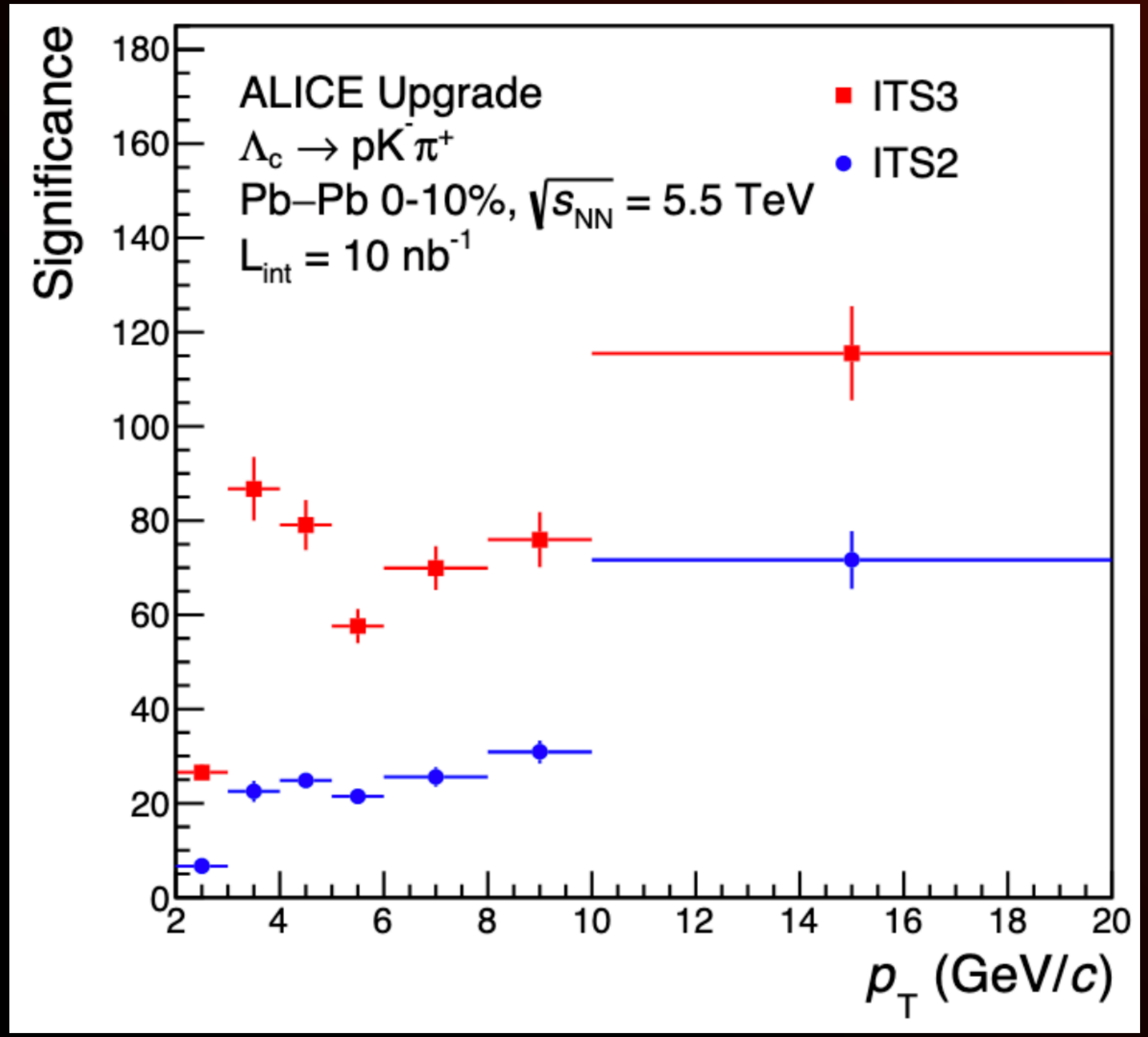
Now – End of LHC Run 4 (2032)

The situation end of Run 4

Inclusive temperature measurement of the QGP



NA60, AIP Conf.Proc. 1322 (2010) 1, 1-10
HADES, Nature Physics 15 (2019) 10, 1040-1045
ALICE, CERN-LHCC-2019-018
CBM, Nucl. Phys. A 982 (2019) 163
NA60+, SPSC-EOI-019
R. Rapp et al., Phys. Lett. B 753 (2016) 568
T. Galatyuk et al., Eur. Phys. J. A52 (5) (2016) 131
Lattice QCD, Phys. Lett. B 795 (2019) 15
SHM, Nature 561 (2018) 7723, 321-330

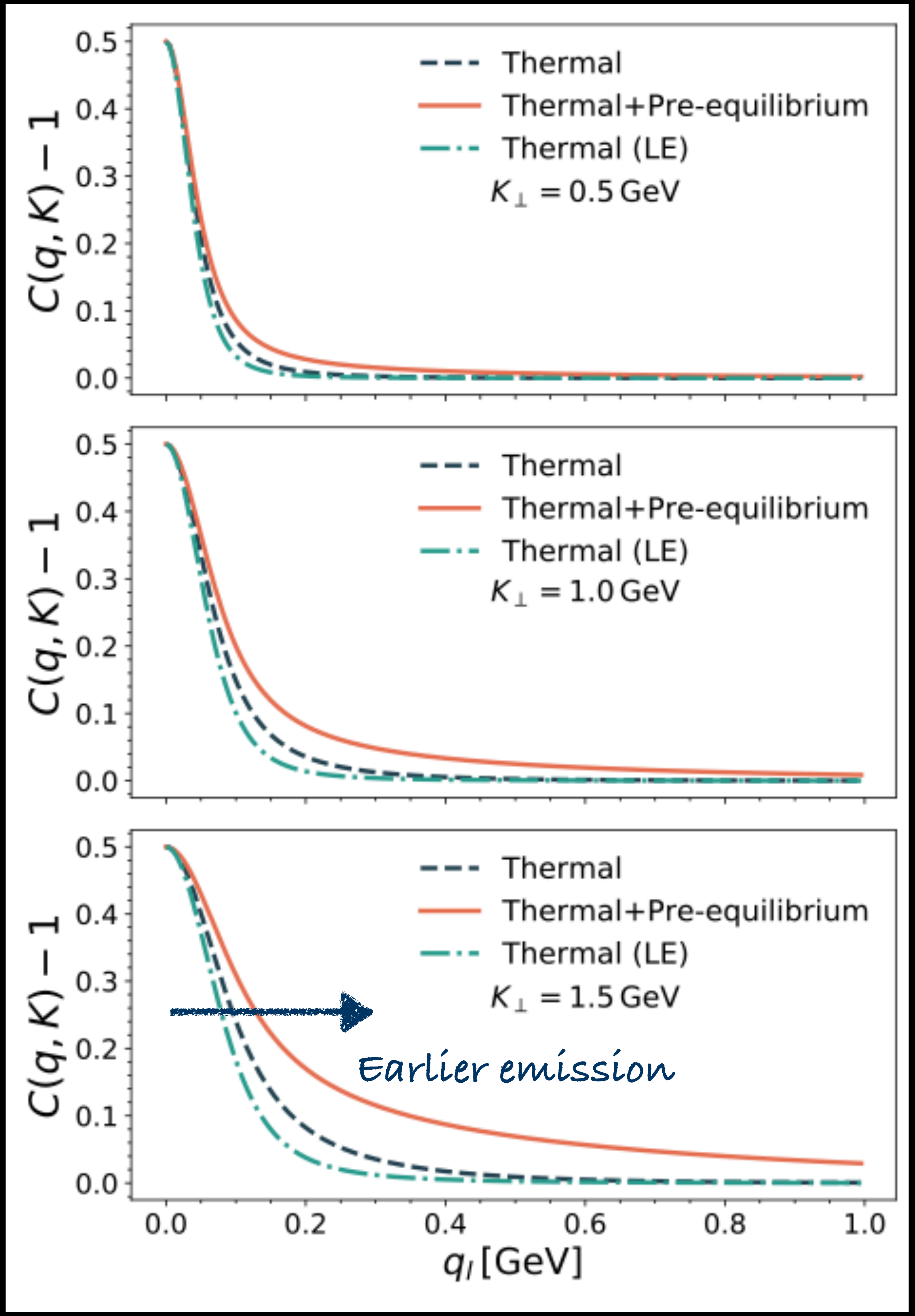


CERN-LHCC-2019-018

Precise measurements of heavy flavour hadron spectra

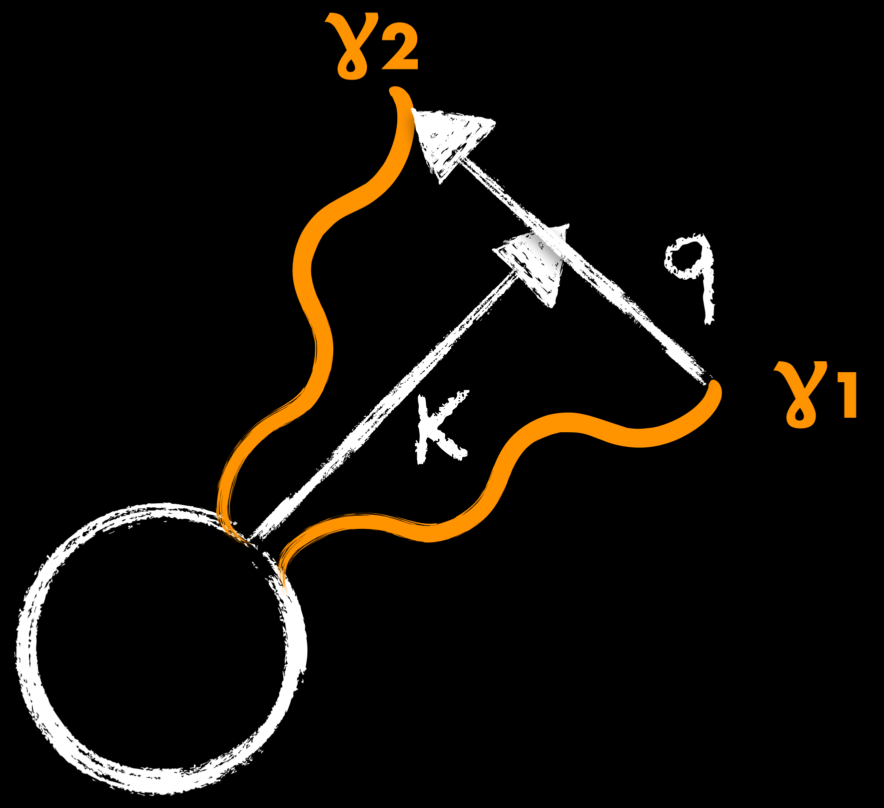
The situation end of Run 4

O. Garcia-Montero et al., *Phys.Rev.C* 102 (2020) 2, 024915

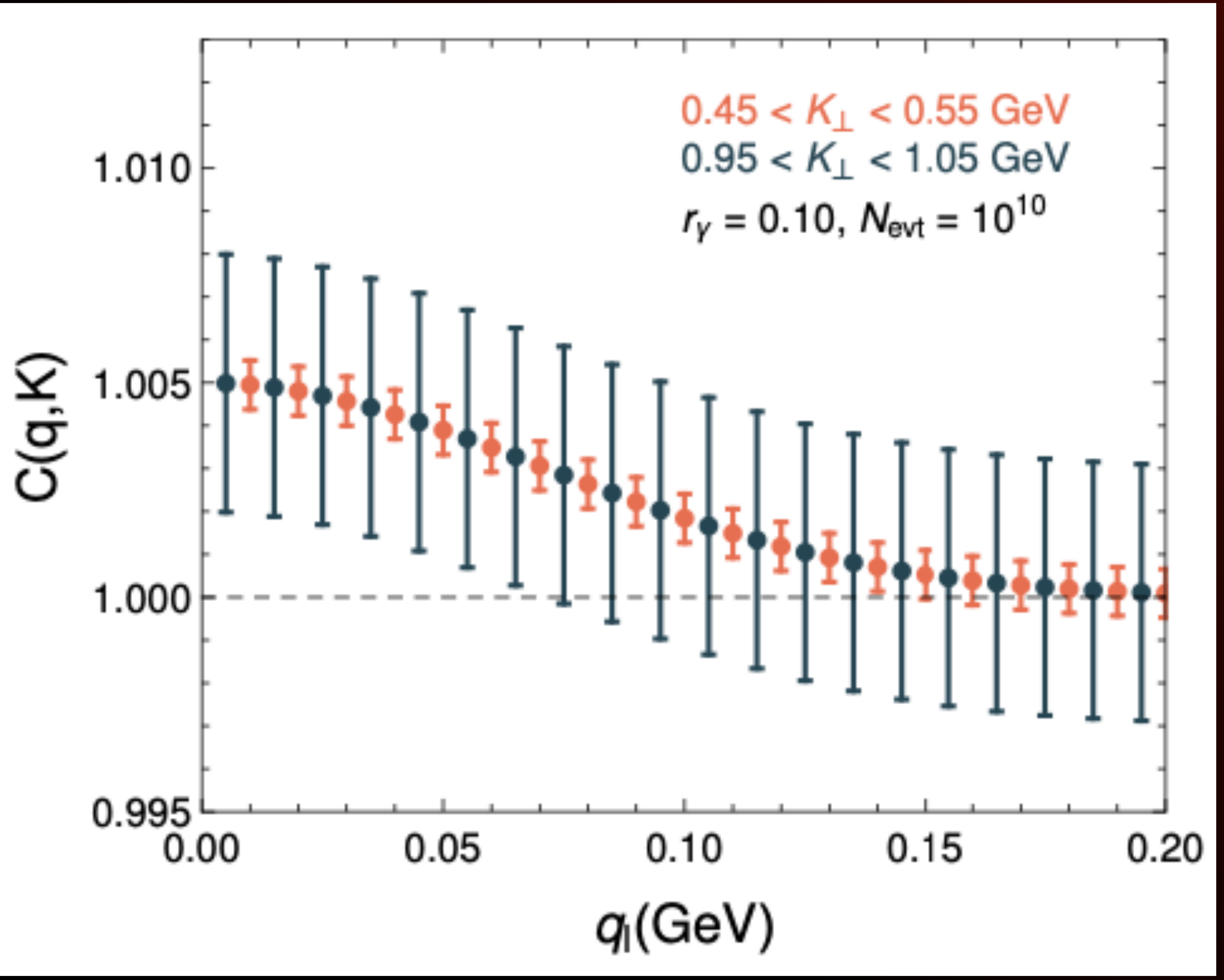


Direct photon HBT correlations

- Sensitivity to size of emitting source (production time)
- Not clear if precision sufficient to disentangle sources

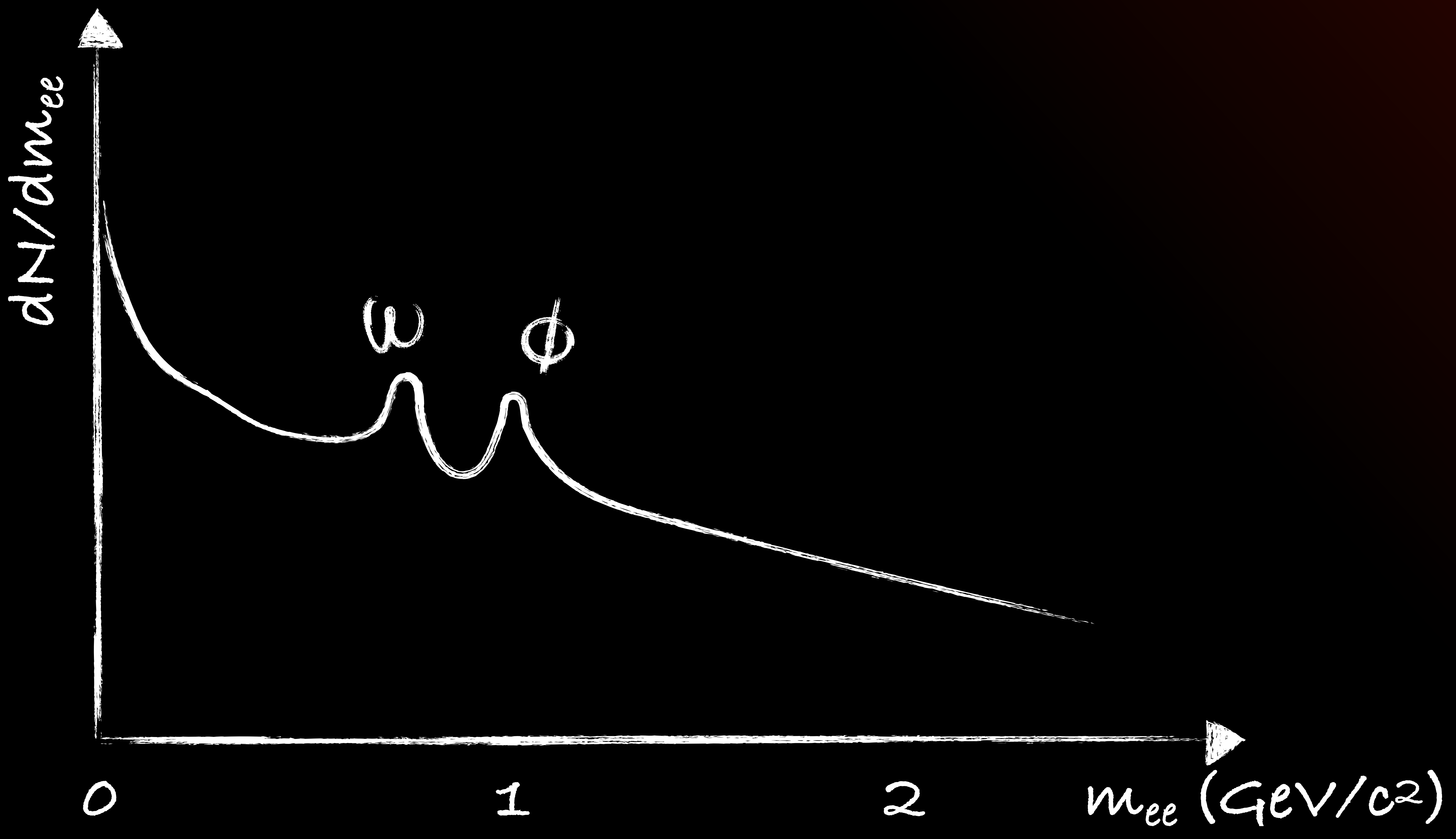


0-20% Pb–Pb @ 2.76 TeV



Where to keep looking?

In the 2030s

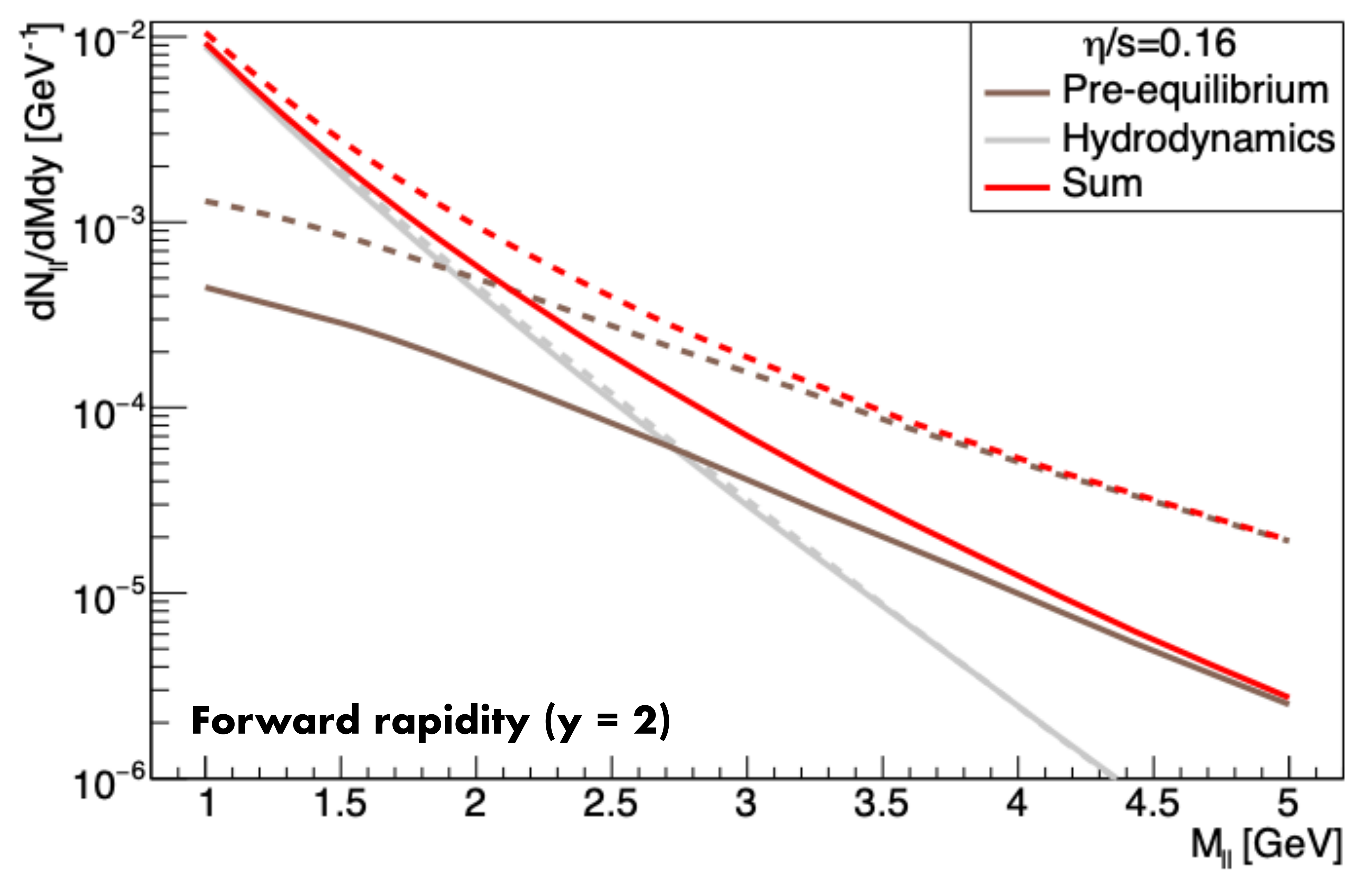

dN/dm_ee
ω
ϕ
0
1
2
m_ee (GeV/c²)

The pre-equilibrium

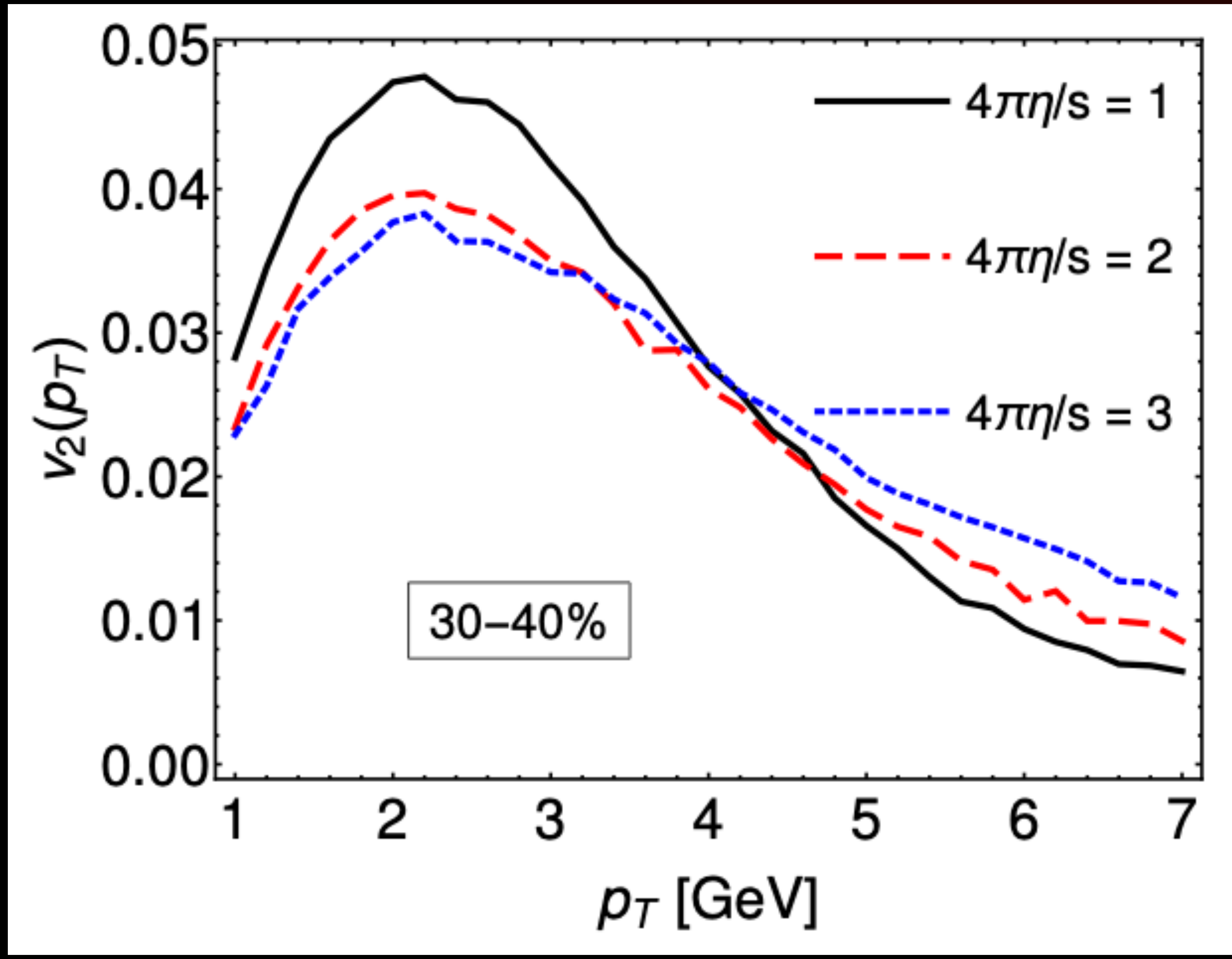
High mass and p_T

Dileptons from earliest collision stage more abundant than the QGP contribution at higher masses

Sensitivity to initial anisotropies and η/s, not accessible with hadronic probes
→ Sensitivity not reached in RUN 3/4 (Now - 2032)



M. Coquet, *et al*, PLB 821 (2021) 136626



B. S. Kasmaei and M. Strickland, PRD 99 (2019) 3, 034015

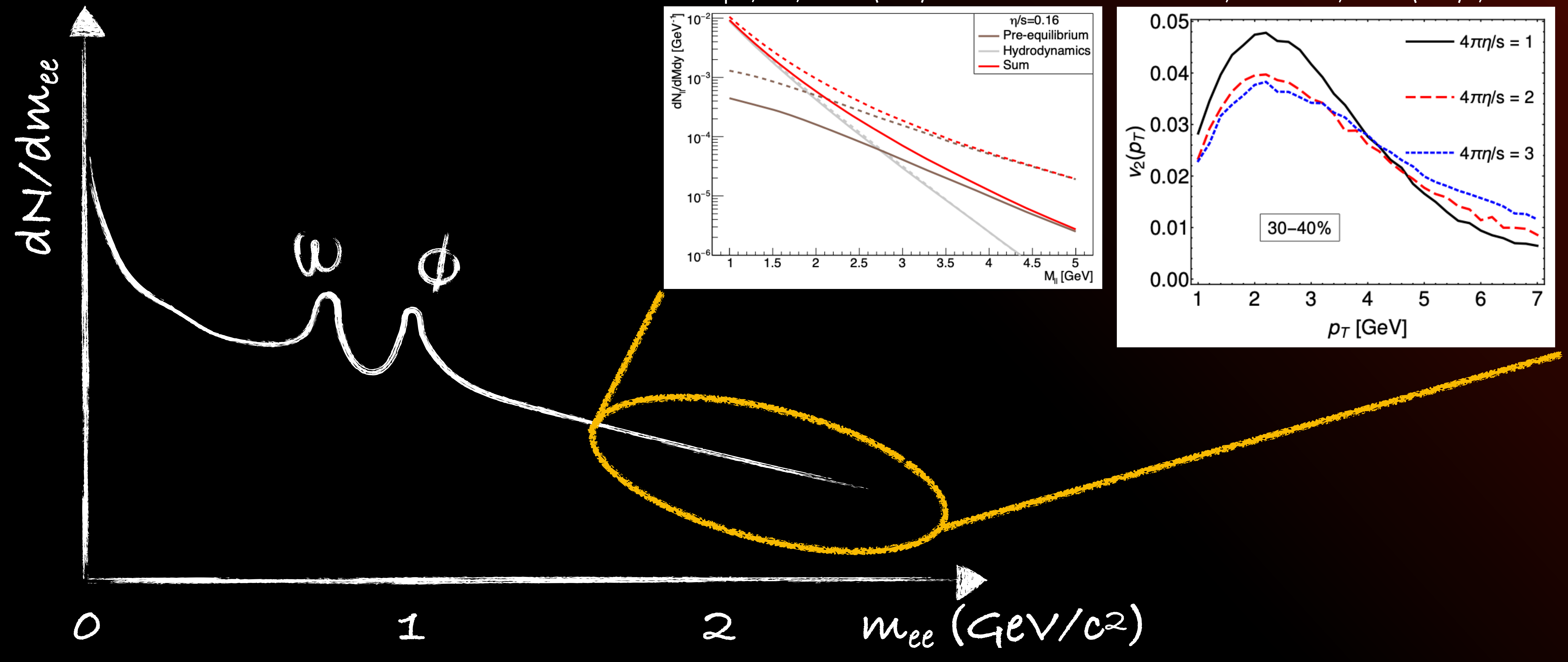
Where to keep looking?

High mass and p_T

Early collision stages &
initial quark momentum anisotropy

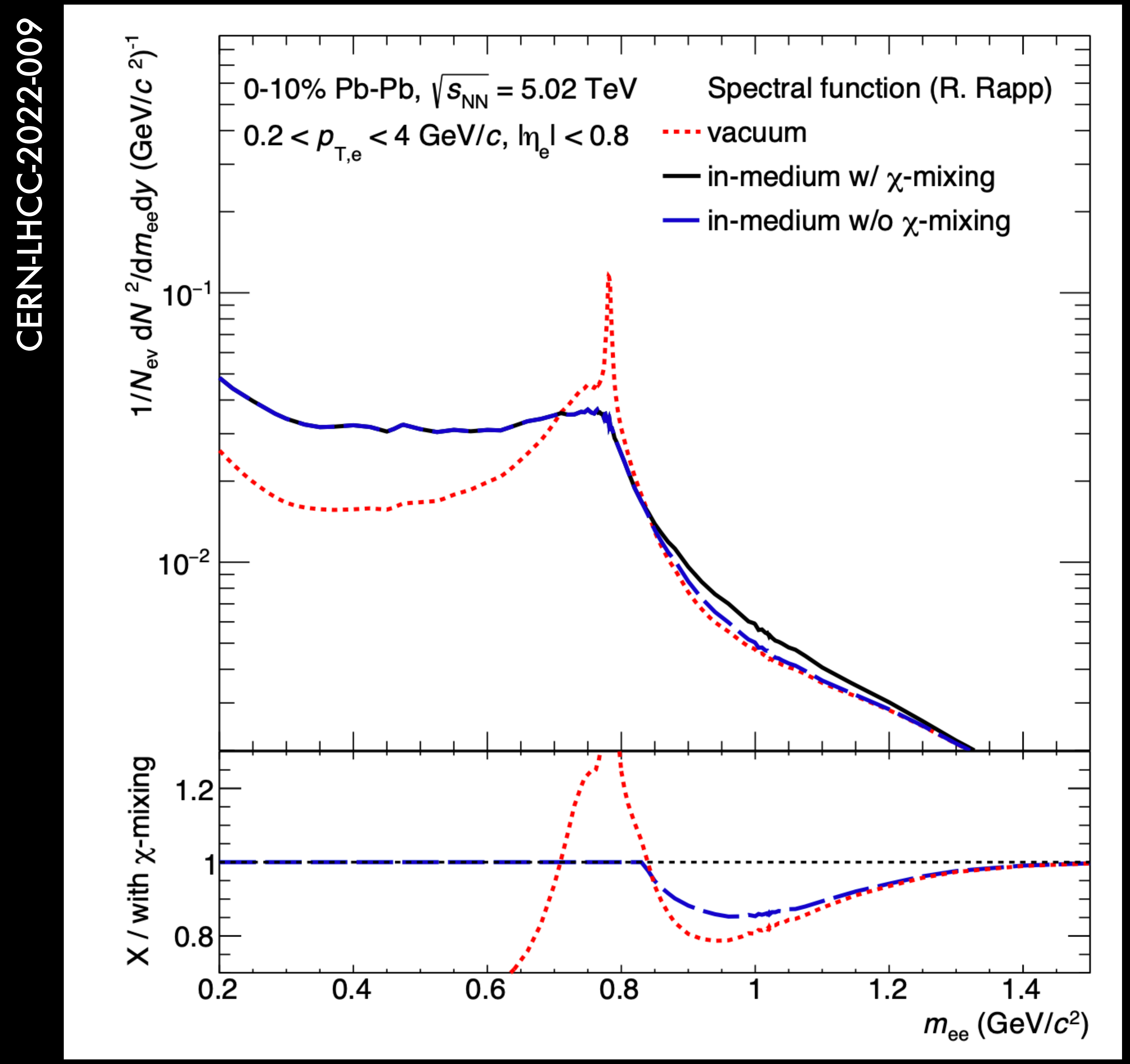
M. Coquet, *et al*, PLB 821 (2021) 136626

B. S. Kasmaei, M. Strickland, PRD 99 (2019) 3, 034015



The hadronic phase

The in medium ρ



Can we learn something from more precision in the ρ spectral function?

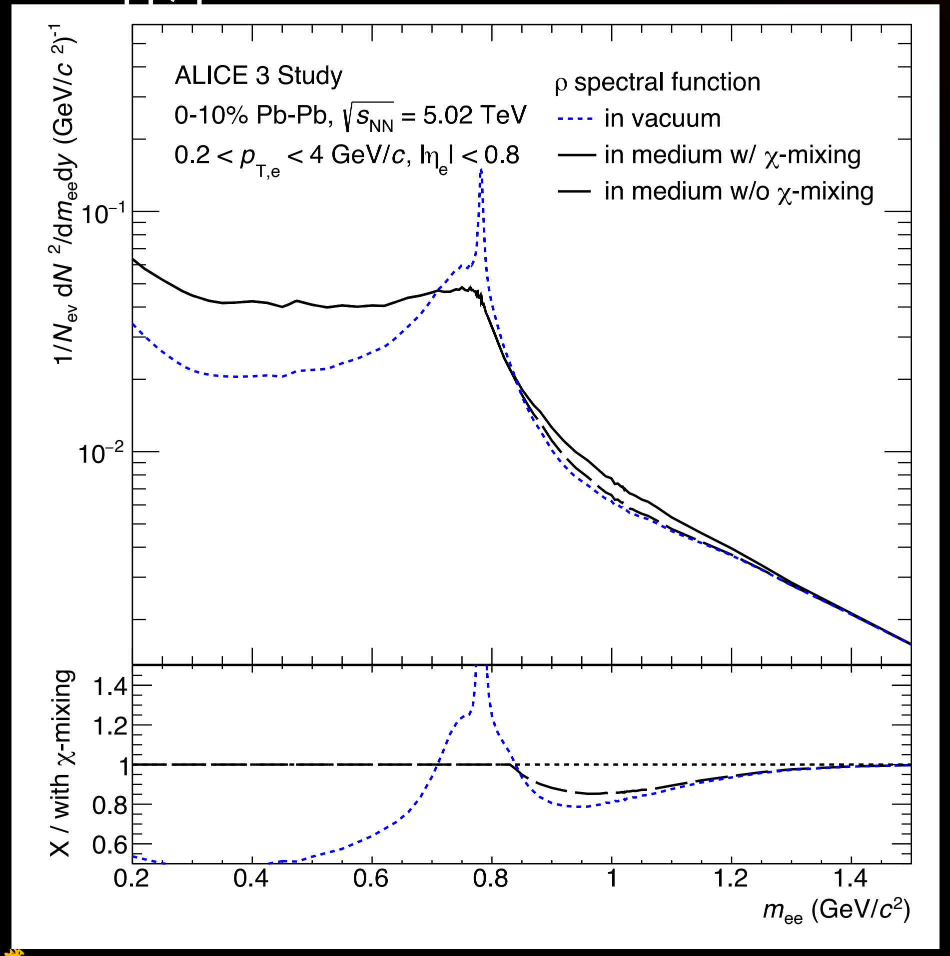
- Chiral mixing of ρ-a_1 changes the shape of dielectron spectrum in $0.9 < m_{ee}$ 1.4 GeV/c^2
- Measurement with precision higher >10% necessary

Where to keep looking?

Intermediate mass

Chiral restoration and medium temperature

R. Rapp, private communication



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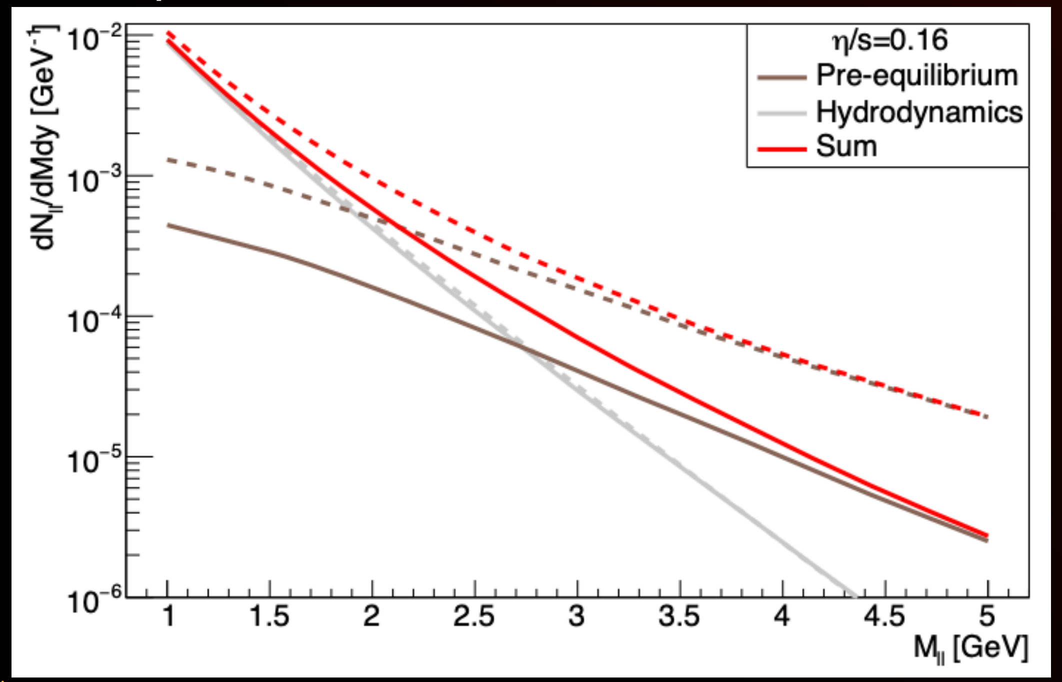
M. Coquet, *et al*, PLB 821 (2021) 136626



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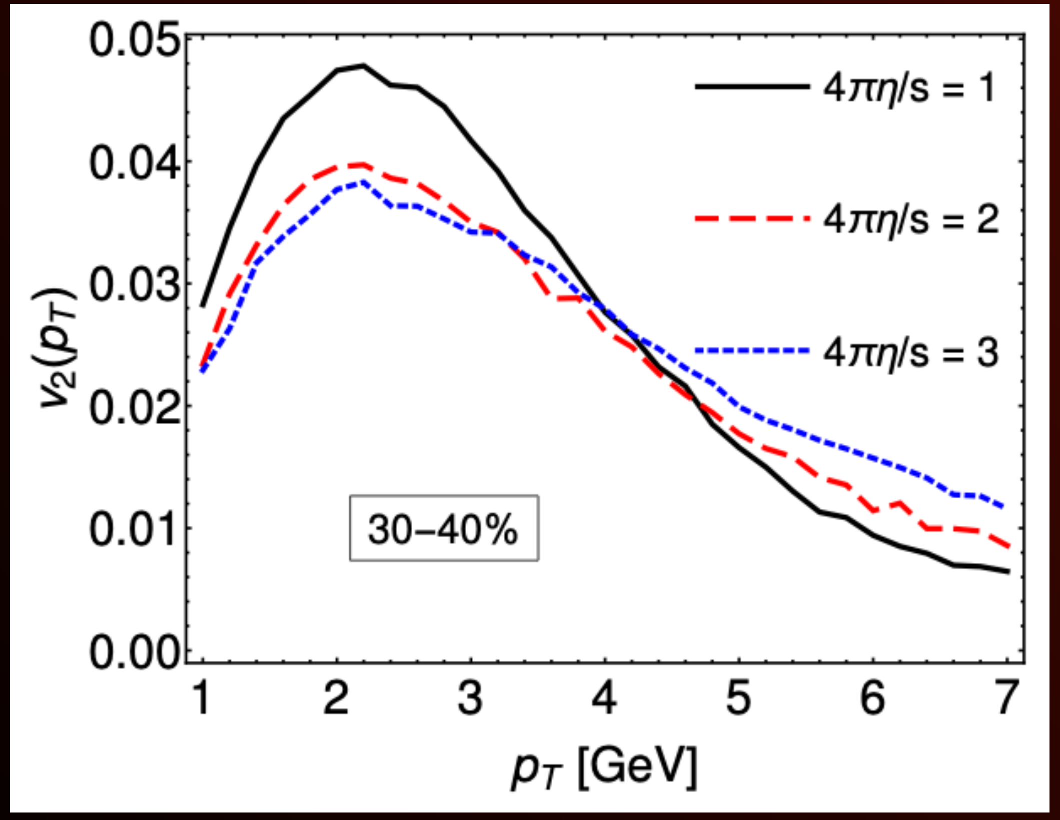
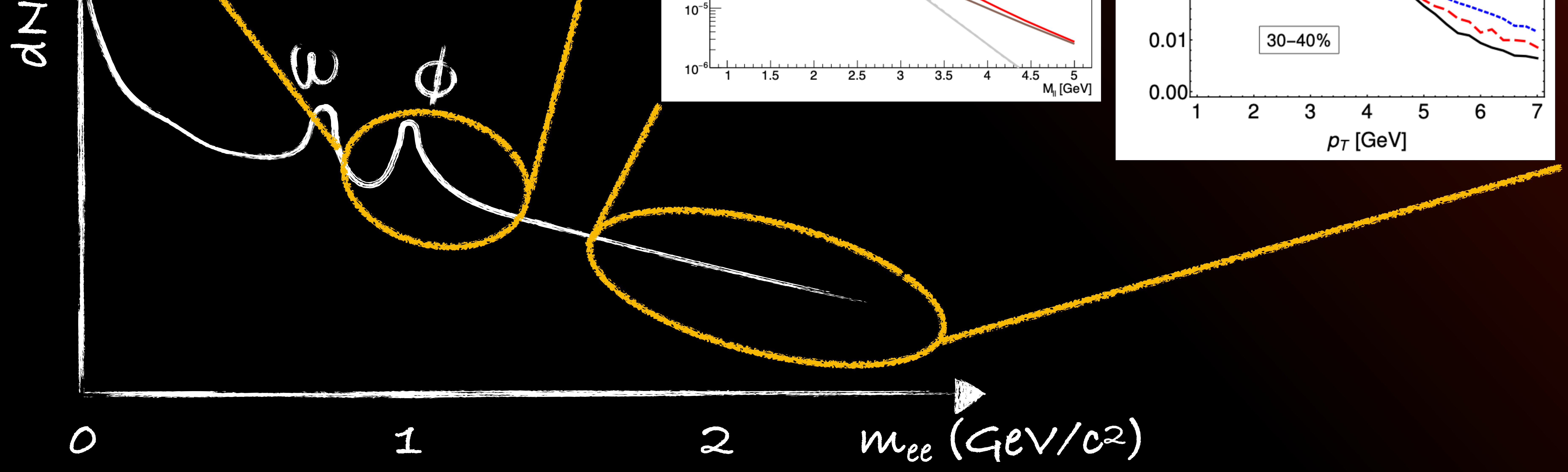




Electric Conductivity

Small mass and p_T

Electric conductivity of the medium

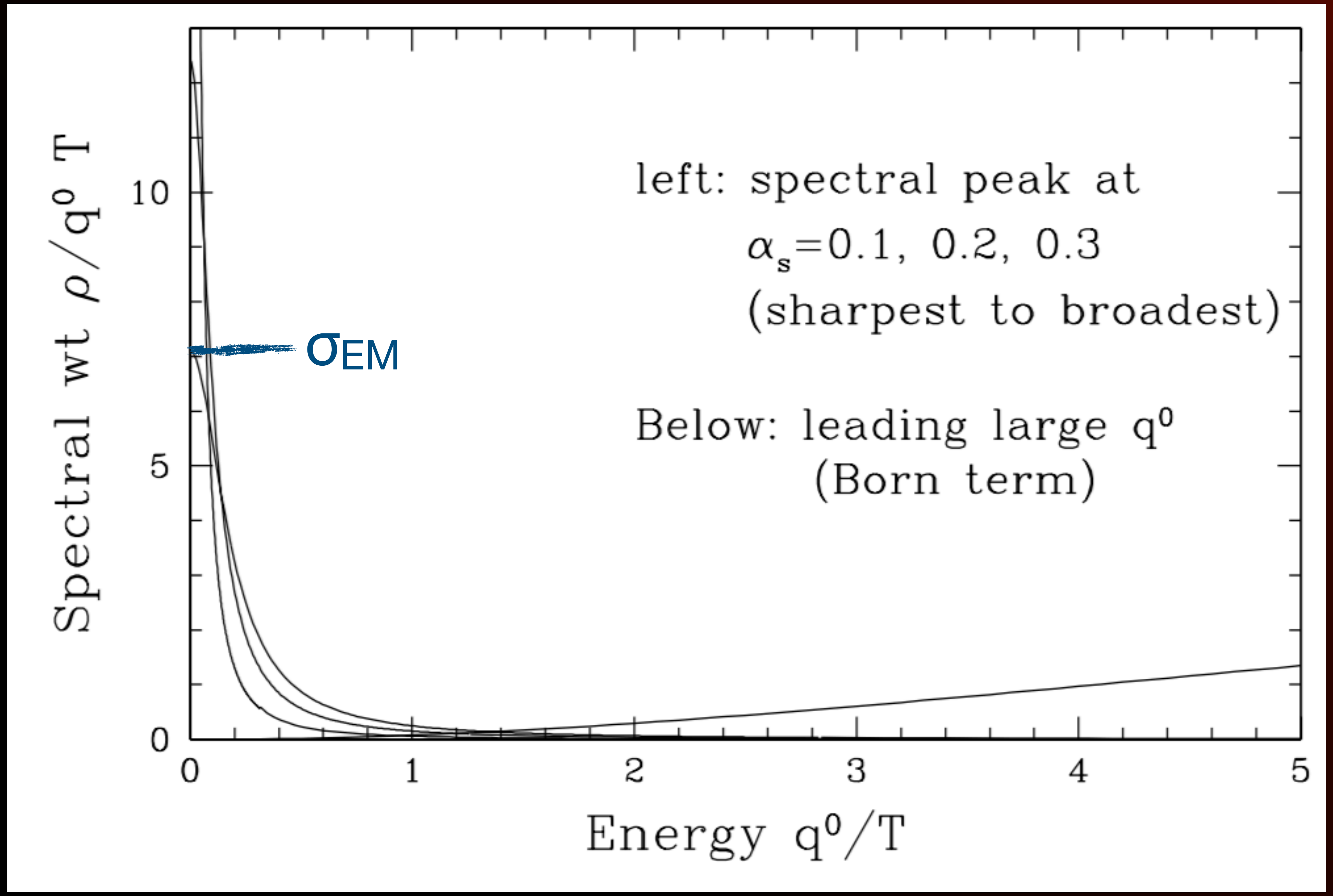
Fundamental property of the medium

- Wide range of theoretical values around
- Input for CME calculations

Connected to dielectron spectral function

$$\sigma_{EM} = -e^2 \lim_{q_0 \to 0} \left(\frac{\partial}{\partial q_o} \mathrm{Im}\Pi(q_0, q = 0, T) \right)$$

Transport peak in the limit of very low mass and p_T



G. D. Moore and J.-M. Robert, arXiv:hep-ph/0607172

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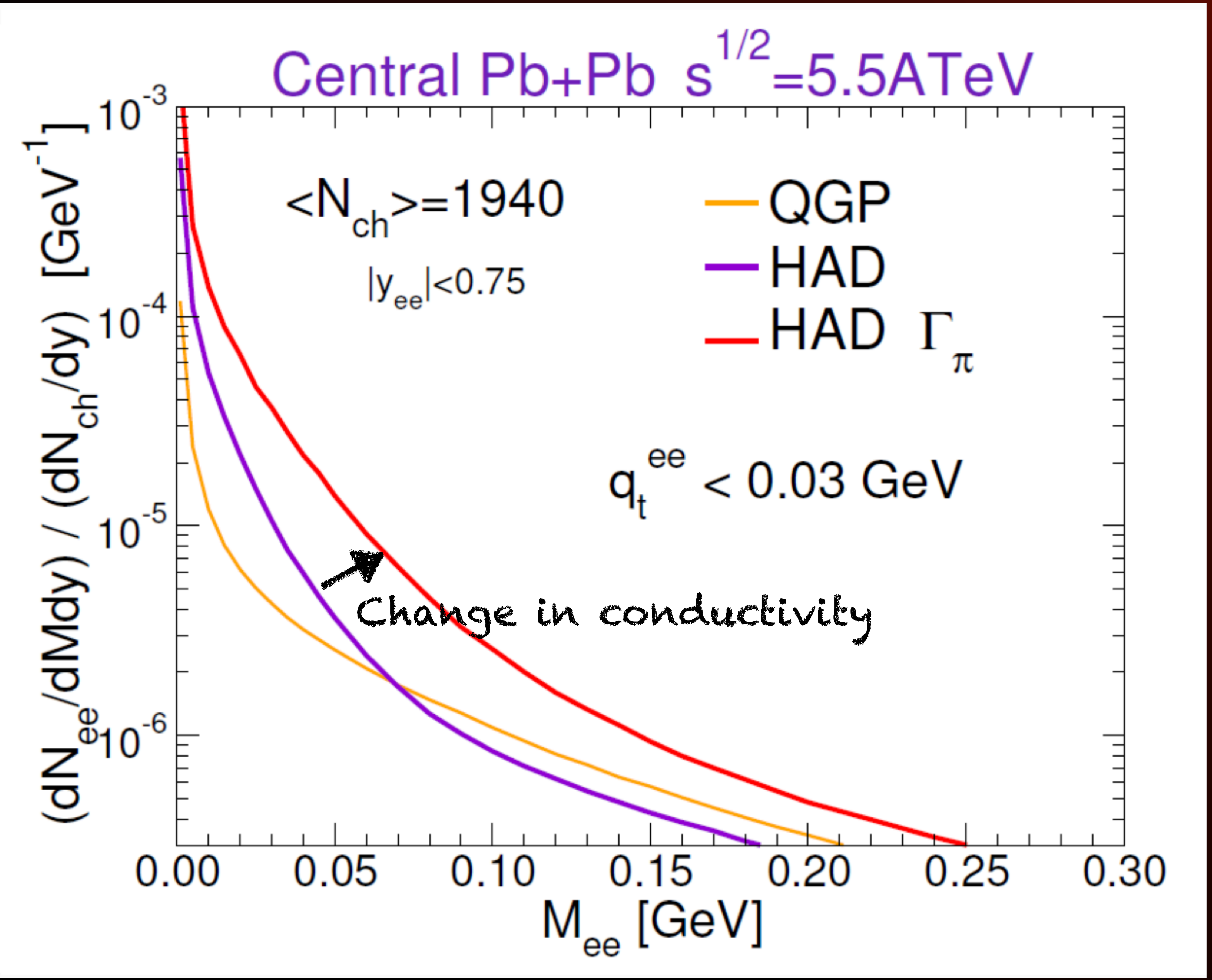
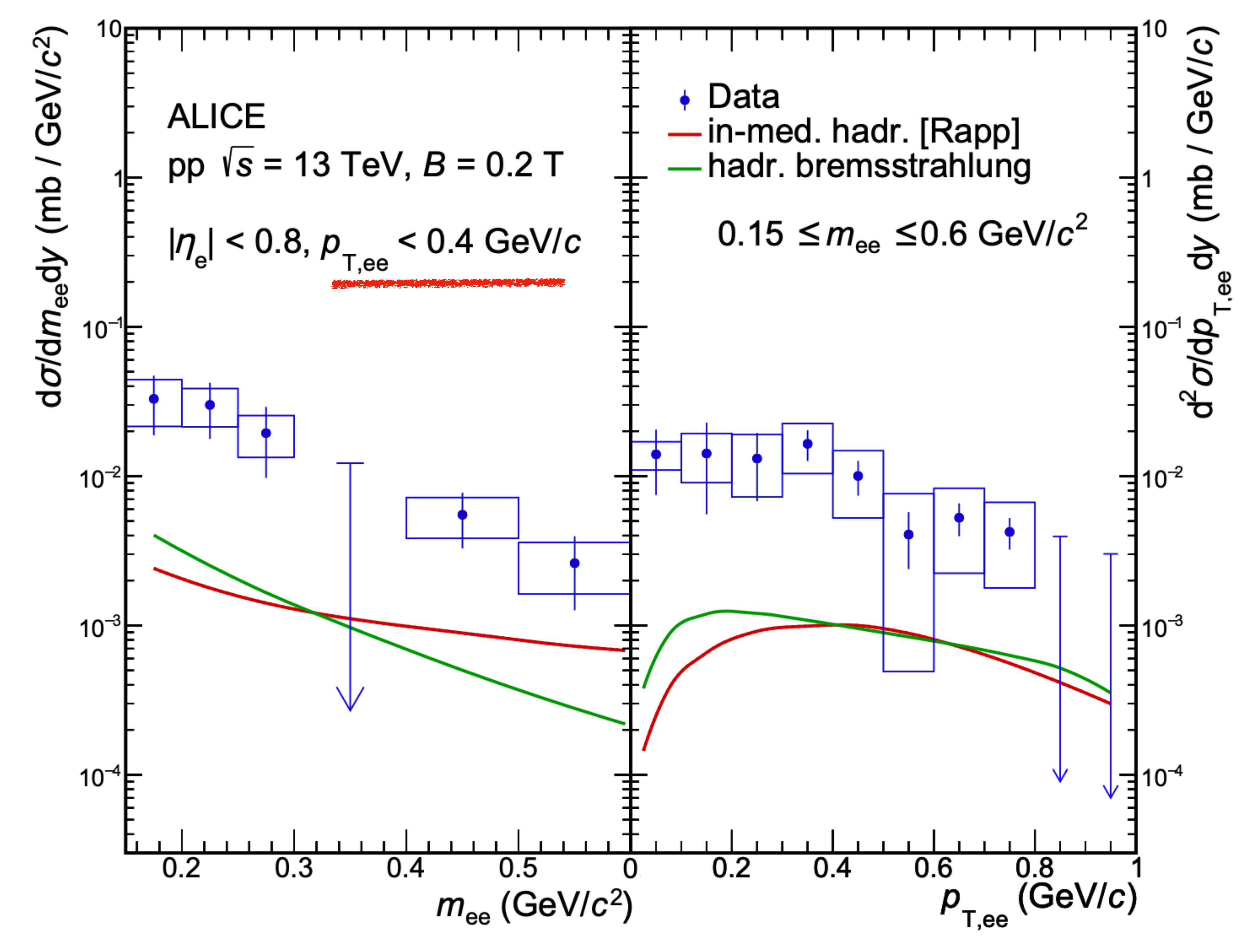
Transport peak in the limit of very low mass and p_T

Sensitivity of spectral function to conductivity not only at $q_0 \to 0$ limit



R. Rapp, EMMI RRTF, 13.9.2021

Soft Dielectrons



pp collisions at $\sqrt{s}$ = 13 TeV

- Lower B field than nominal → smaller p_T possible
- Excess of low p_T dielectrons observed
- Not described by thermal radiation/hadronic bremsstrahlung

At very low p_T: γ produced mainly via inner Bremsstrahlung

Can be calculated via Low theorem if in- and out-going particles can be measured

Where to keep looking?

The softest Photons

Experiment	Year	Collision energy	Photon p_T	Photon/Brems Ratio	Detection method	Reference
π^+p	1979	10.5 GeV	$p_T < 30$ MeV/c	**1.25 ± 0.25**	Bubble chamber	Goshawk et al., PRL 43,1065 (1979)
K^+p WA27, CERN	1984	70 GeV	$p_T < 60$ MeV/c	**4.0 ± 0.8**	Bubble chamber (BEBC)	Chiliapnikov et al., PLB 141, 276 (1984)
π^+p CERN, EHS, NA22	1991	250 GeV	$p_T < 40$ MeV/c	**6.4 ± 1.6**	Bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
K^+p CERN, EHS, NA22	1991	250 GeV	$p_T < 40$ MeV/c	**6.9 ± 1.3**	Bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
π^-p CERN, WA83, OMEGA	1993	280 GeV	$p_T < 10$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	**7.9 ± 1.4**	Calorimeter	Banerjee et al., PLB 305, 182 (1993)
p–Be	1993	450 GeV	$p_T < 20$ MeV/c	**< 2**	Pair conversion, calorimeter	Antos et al., Z. Phys. C 59, 547 (1993)
p–Be, p–W	1996	18 GeV	$p_T < 50$ MeV/c	**< 2.65**	Calorimeter	Lissauer et al., PRC 54, 1918 (1996)
π^-p CERN, WA91, OMEGA	1997	280 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	**7.8 ± 1.5**	Pair conversion	Belogianni et al., PLB 408, 487 (1997)
π^-p CERN, WA91, OMEGA	2002	280 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	**5.3 ± 1.0**	Pair conversion	Belogianni et al., PLB 548, 122 (2002)
pp CERN, WA102, OMEGA	2002	450 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	**4.2 ± 0.8**	Pair conversion	Belogianni et al., PLB 548, 129 (2002)
$e^+e^- \to 2$ jets CERN, Delphi	2006	91 GeV (CM)	$p_T < 80$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	**4.0 ± 0.3 ± 1.0**	Pair conversion	DELPHI, EPJC 47, 273 (2006)
$e^+e^- \to \mu^+\mu^-$ CERN, Delphi	2008	91 GeV (CM)	$p_T < 80$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	**~1**	Pair conversion	DELPHI, EPJC 57, 499 (2008)

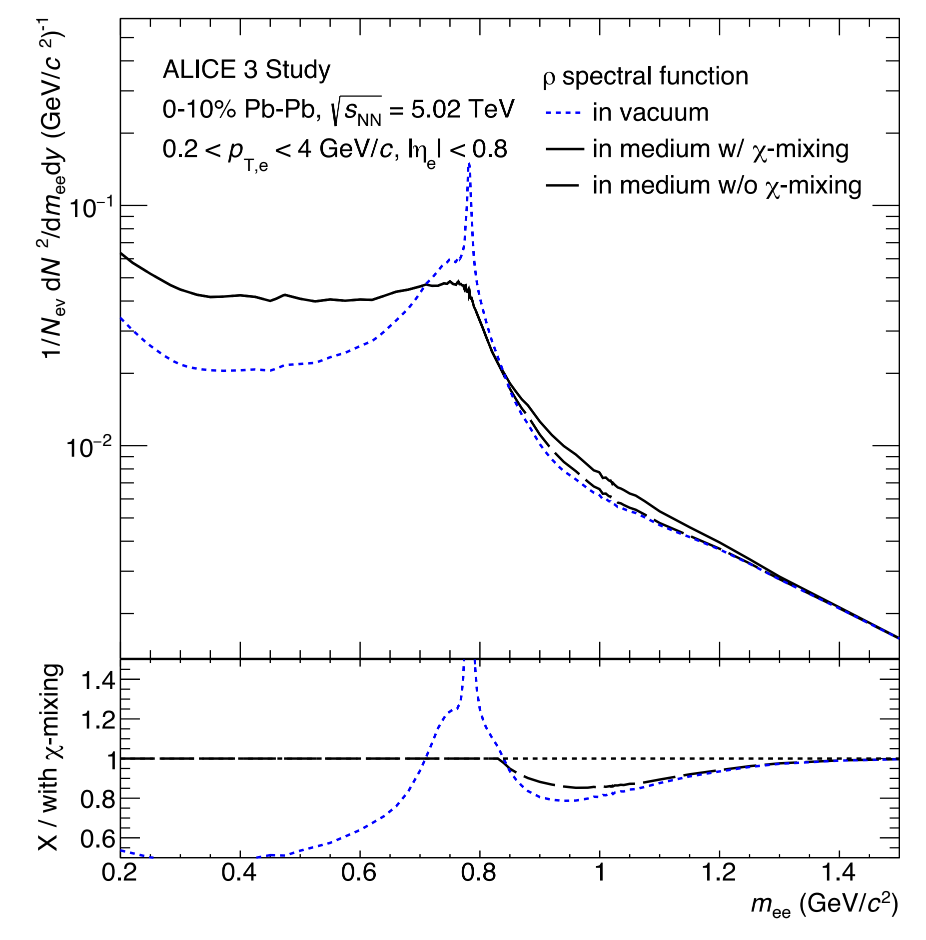
K. Reygers EMMI RRTF, Sep 14th 2021

Where to keep looking?

Intermediate mass

Chiral restoration and medium temperature

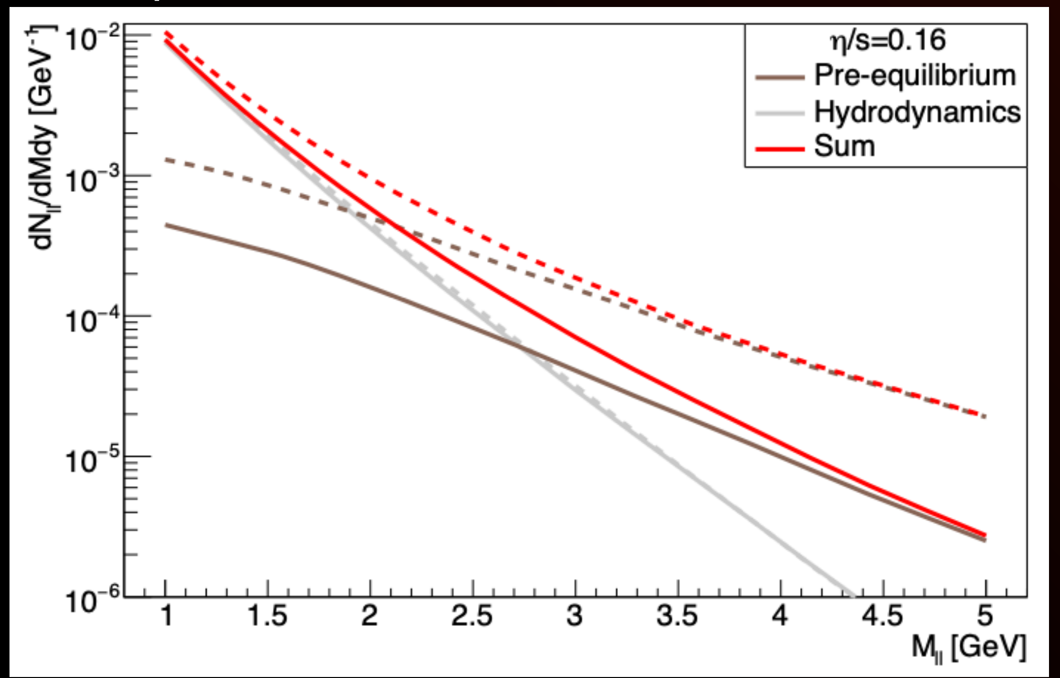
R. Rapp, private communication



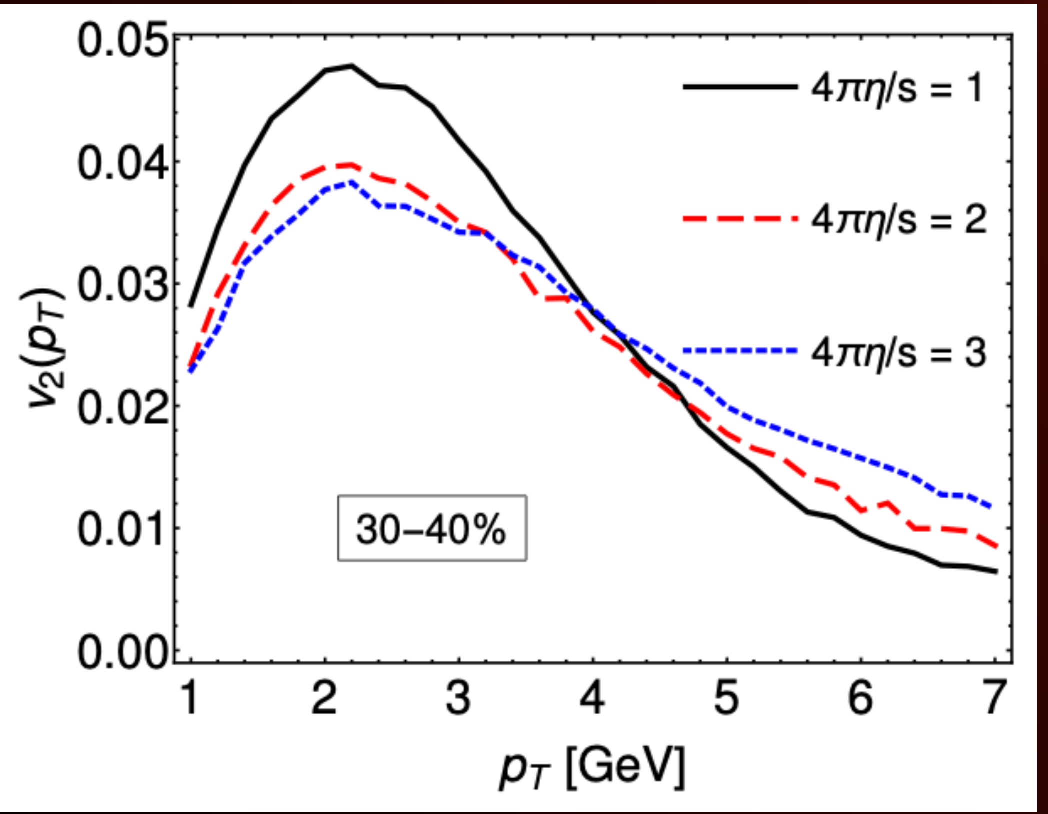
High mass and p_T

Early collision stages & initial quark momentum anisotropy

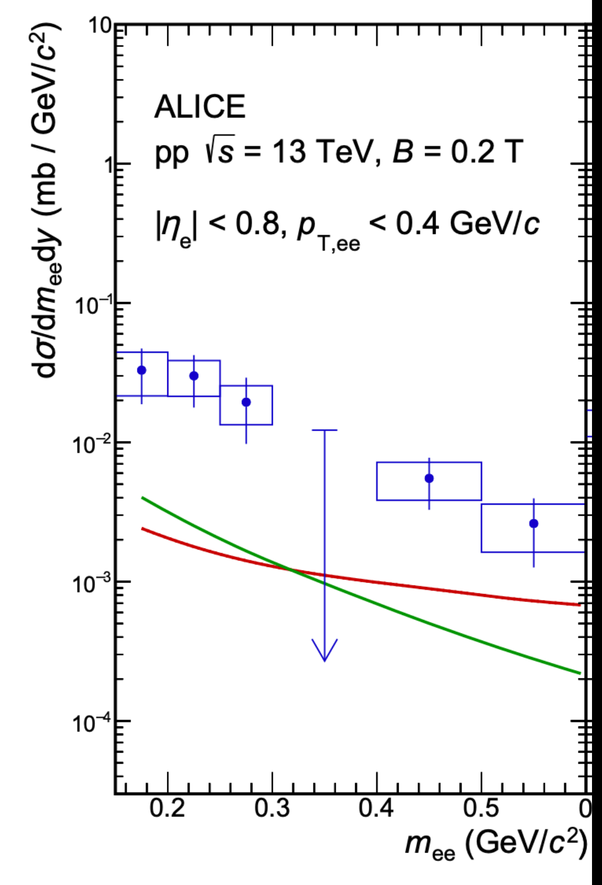
M. Coquet, *et al*, PLB 821 (2021) 136626

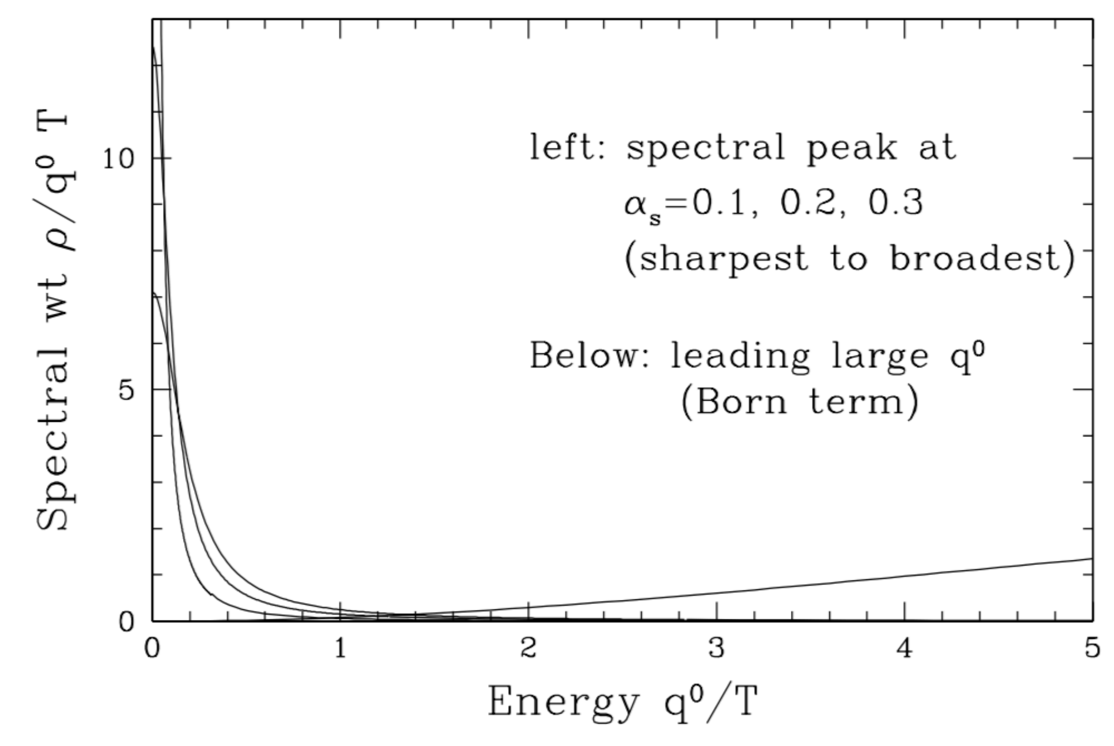


B. S. Kasmaei, M. Strickland, PRD 99 (2019) 3, 034015

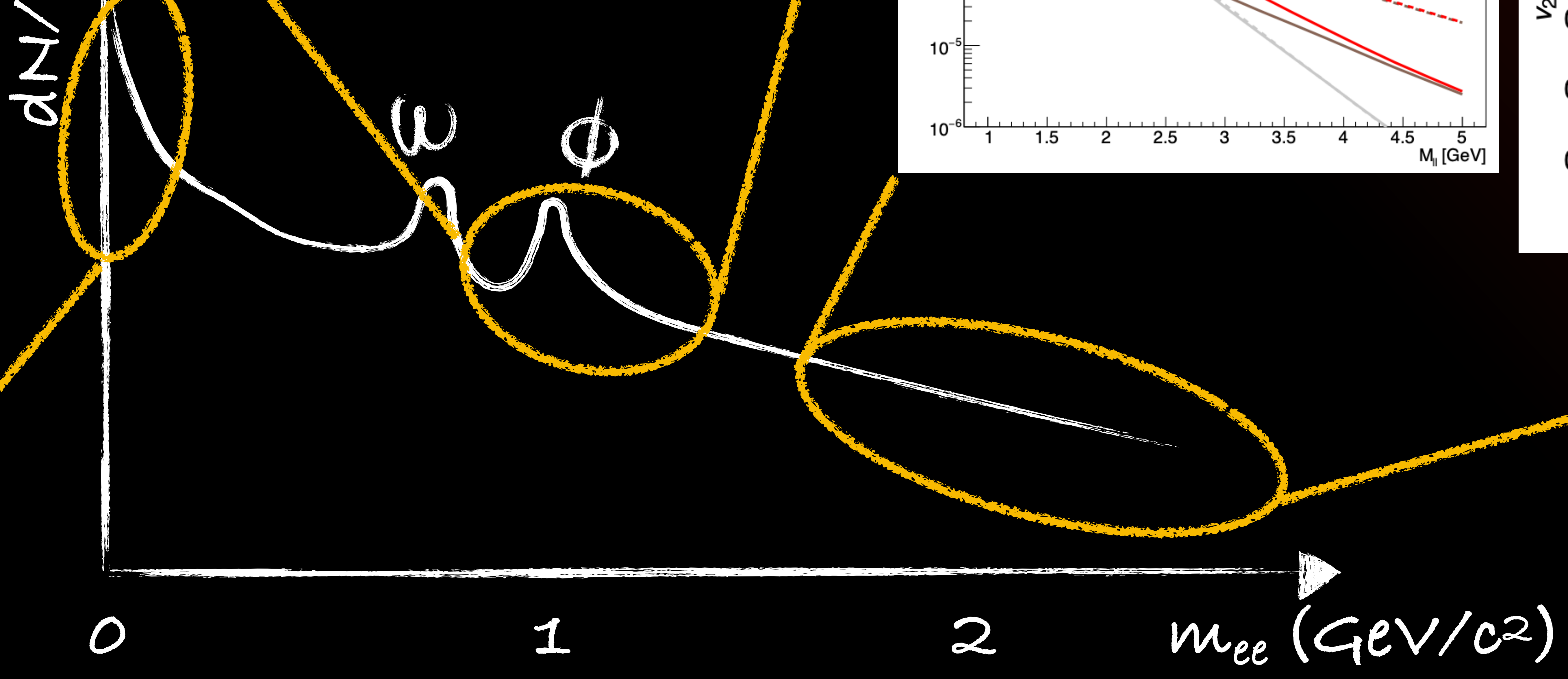


ALICE, *Phys.Rev.Lett.* 127 (2021) 4, 042302





G. D. Moore and J.-M. Robert, arXiv:hep-ph/0607172



Very low mass and pair p_T

Electric conductivity and soft (virtual) photons

Thinking about an experiment

What do we need?

- Sufficient statistics for multi dimensional analysis
- Measure photons and electrons with high efficiency and accuracy
- Rejection of heavy flavour contribution in dielectrons
- Low p_T photon reconstruction

How do we get that?

- Possibility to run at high rates
- Particle identification and tracking over a broad momentum range and large acceptance
- Photon measurements via conversion and calorimetry

ALICE 3

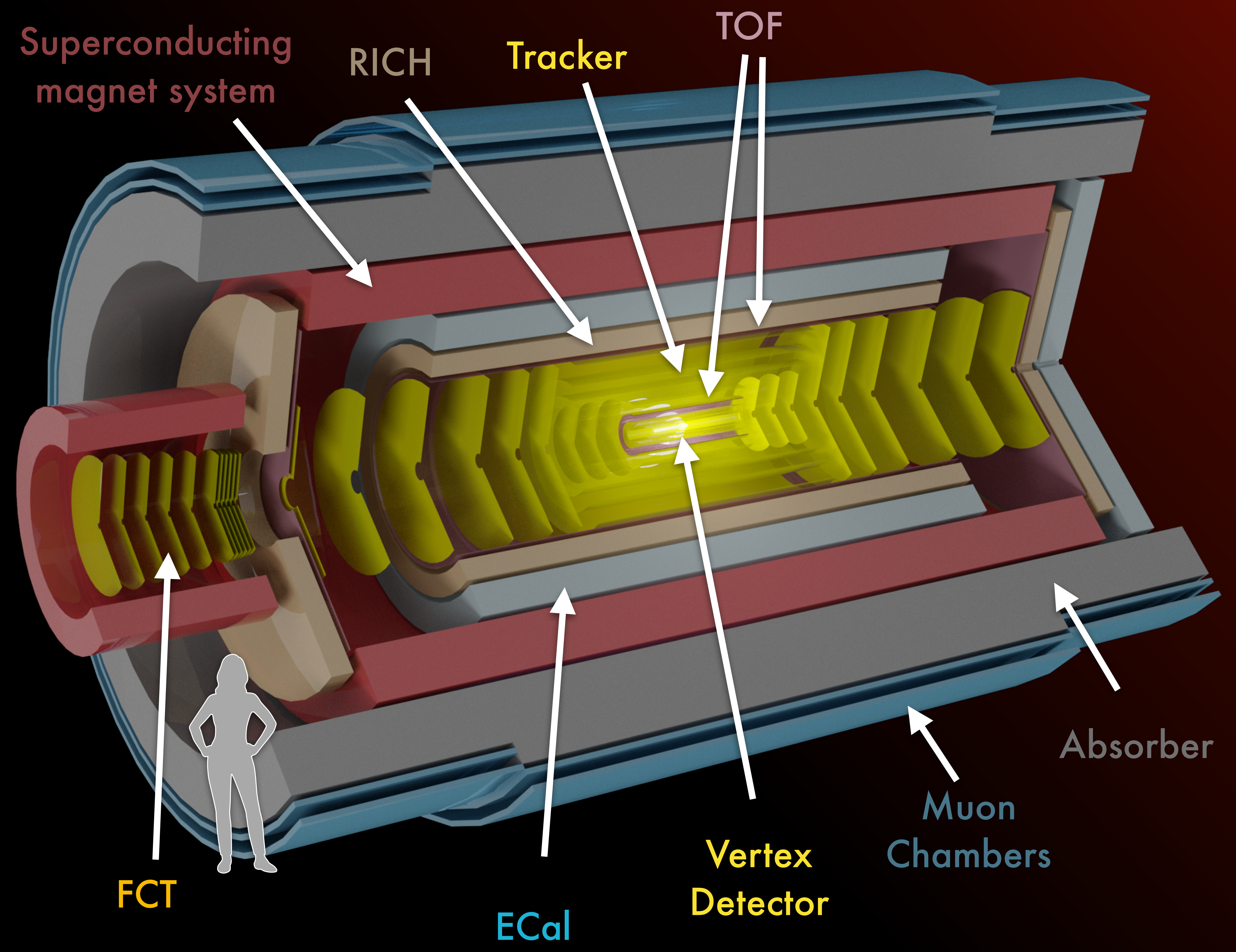
High precision tracking

Electron Identification

Electromagnetic Calorimeter

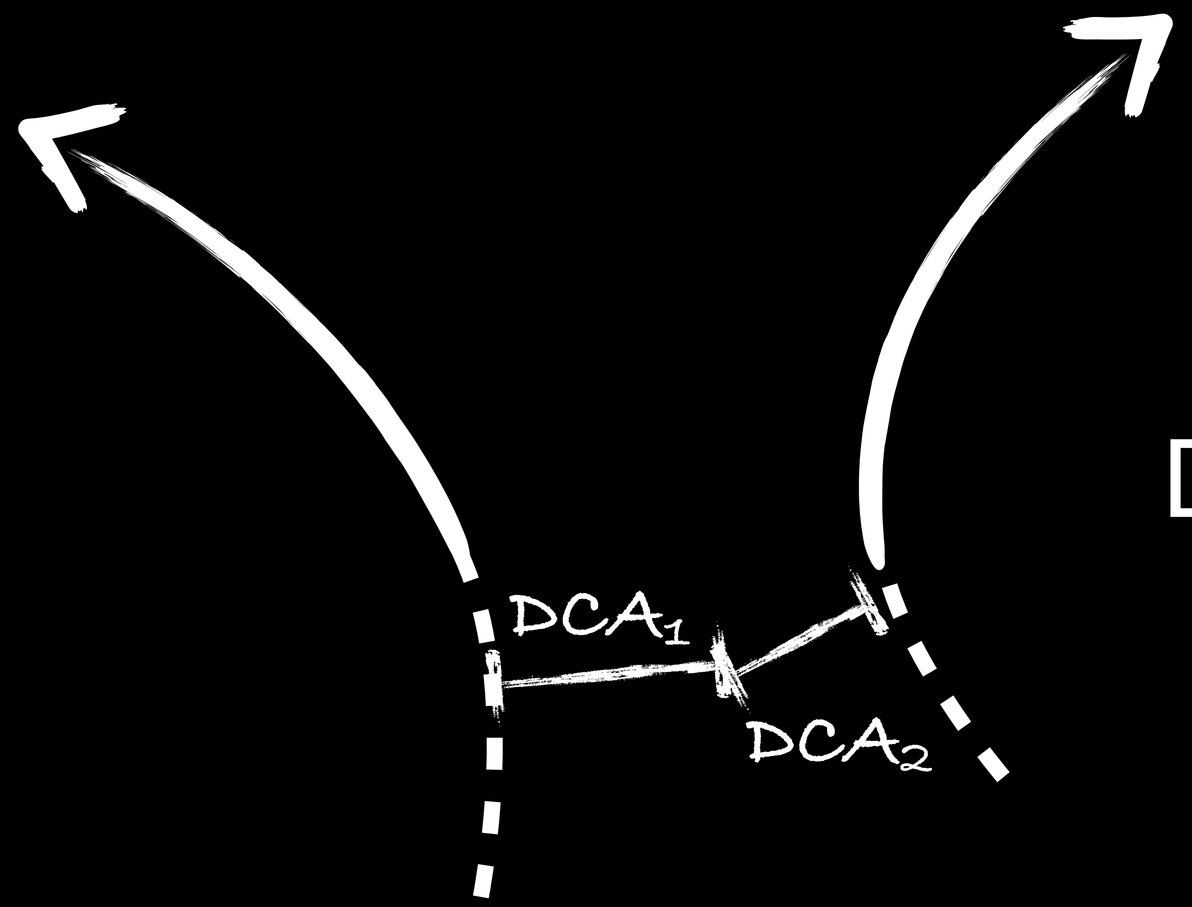
Forward Photon Converter

Talk by Jochen Klein



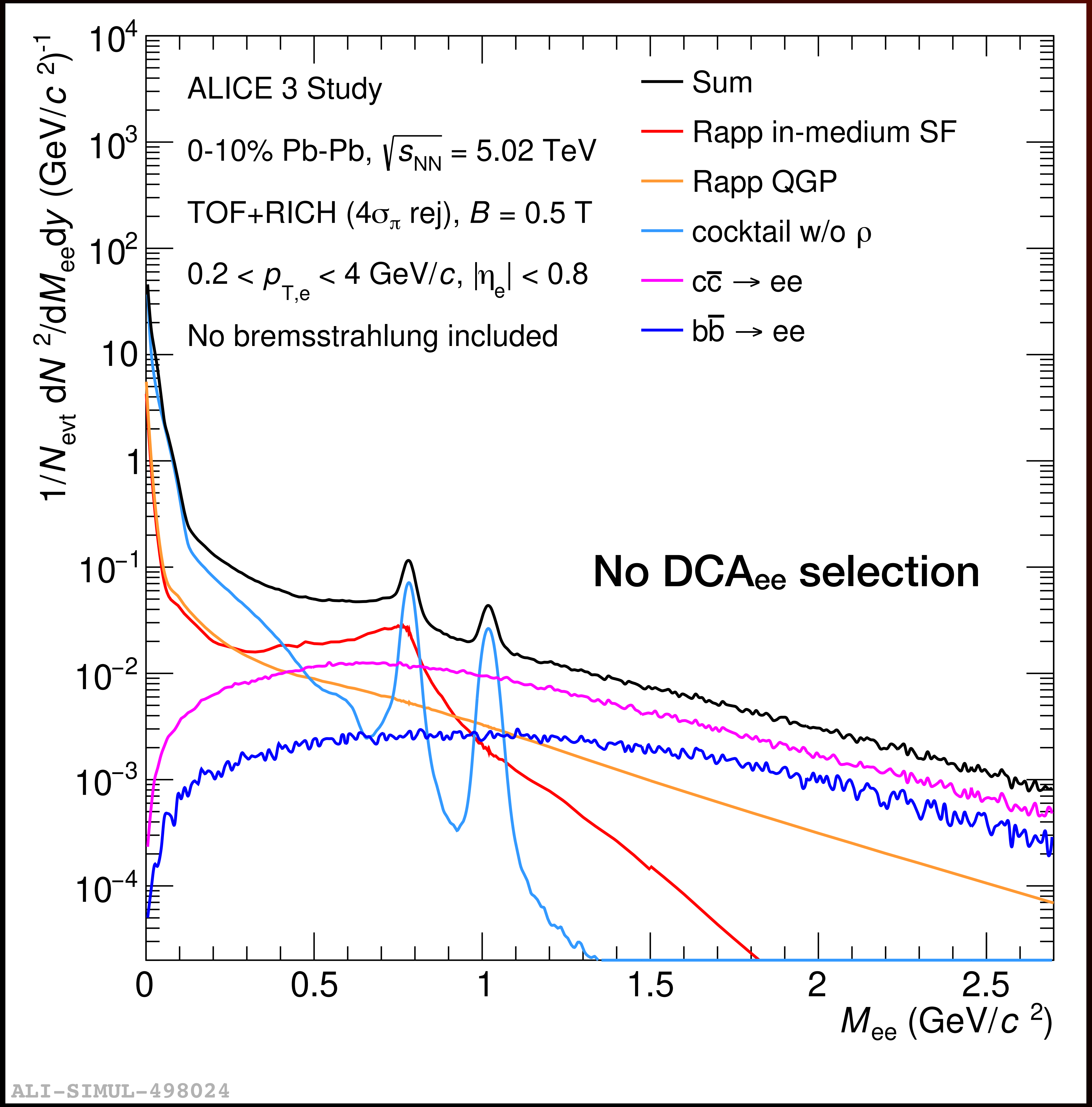
Dielectrons

Use pair distance of closest approach (DCA_{ee}) to reject heavy-flavour backgrounds



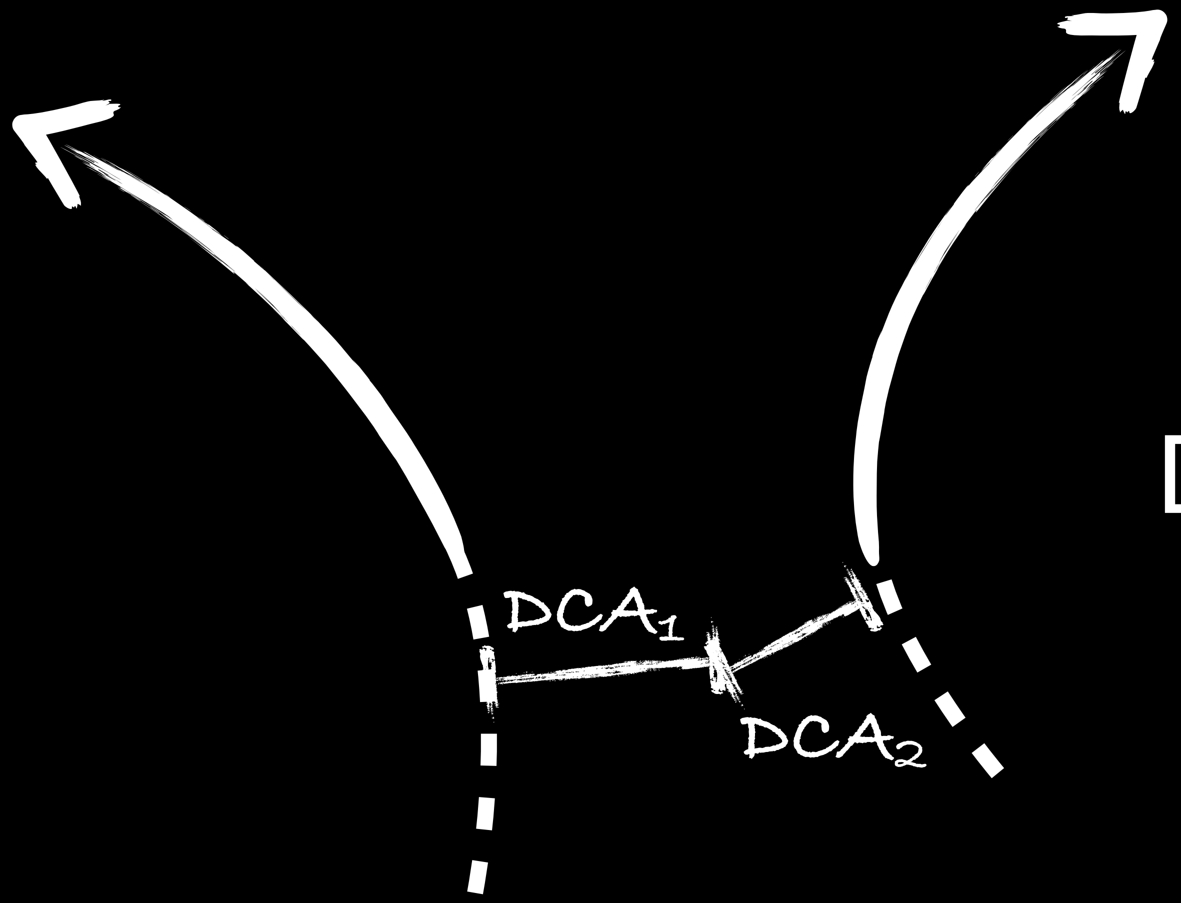
$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

CERN-LHCC-2022-009



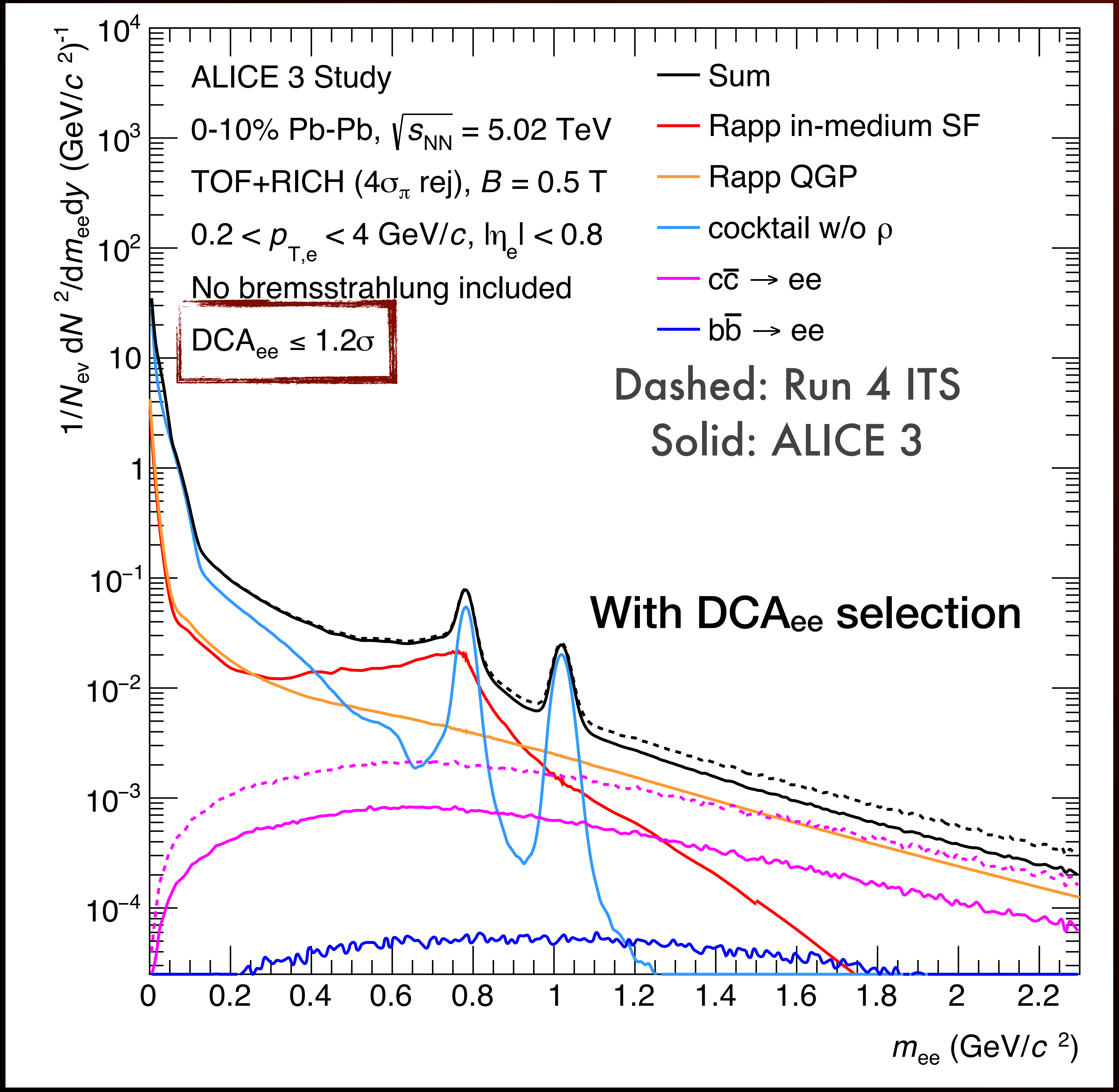
Dielectrons

Use pair distance of closest approach (DCA_{ee}) to reject heavy-flavour backgrounds



$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

CERN-LHCC-2022-009



Thermal dielectron contributions dominant at m_{ee} > 400 MeV/c² (except peak of ω/ϕ)

Excess yield

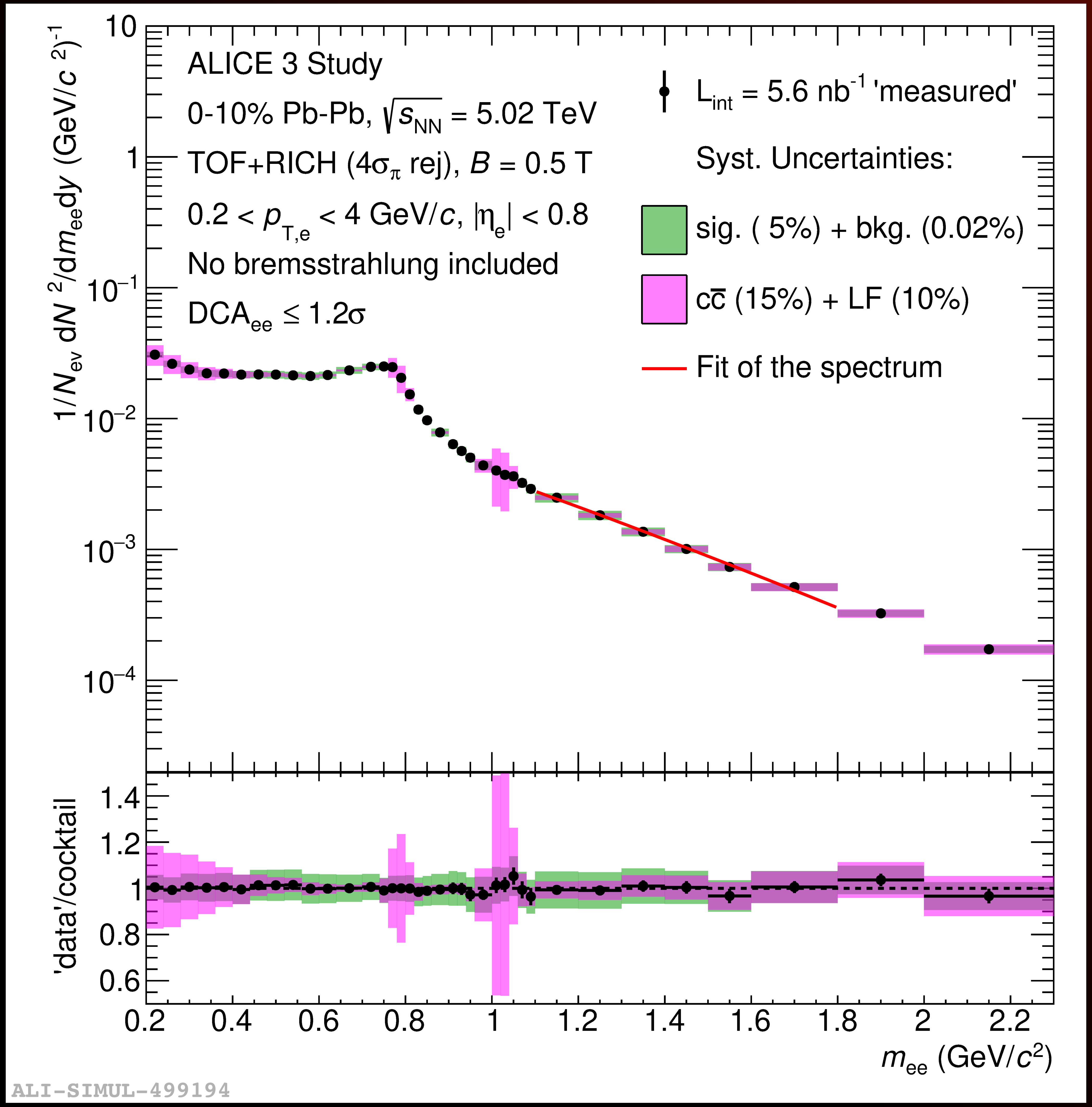
The Temperature fit

Thermal spectrum from QGP and hadron gas after subtraction of hadronic components

Temperature estimation via exponential fit $\propto (m_{ee}T)^{\frac{3}{2}}\exp(-m_{ee}/T)$

In region dominated by QGP radiation

CERN-LHCC-2022-009



Excess yield

The Temperature fits

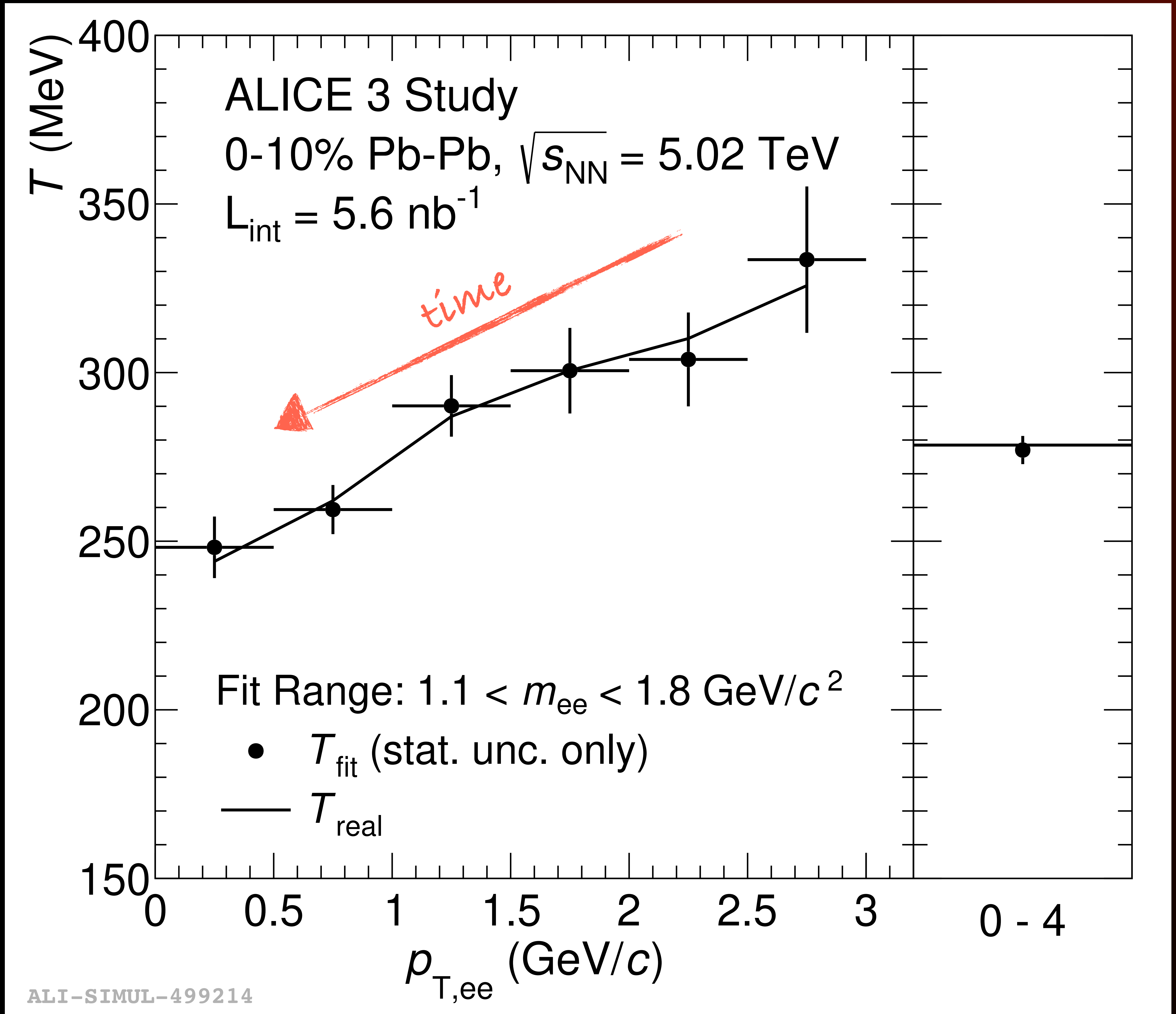
Differential analysis in p_T gives access to early phase of the collision

Probe time evolution of the QGP

Complementary measurement to photon spectrum

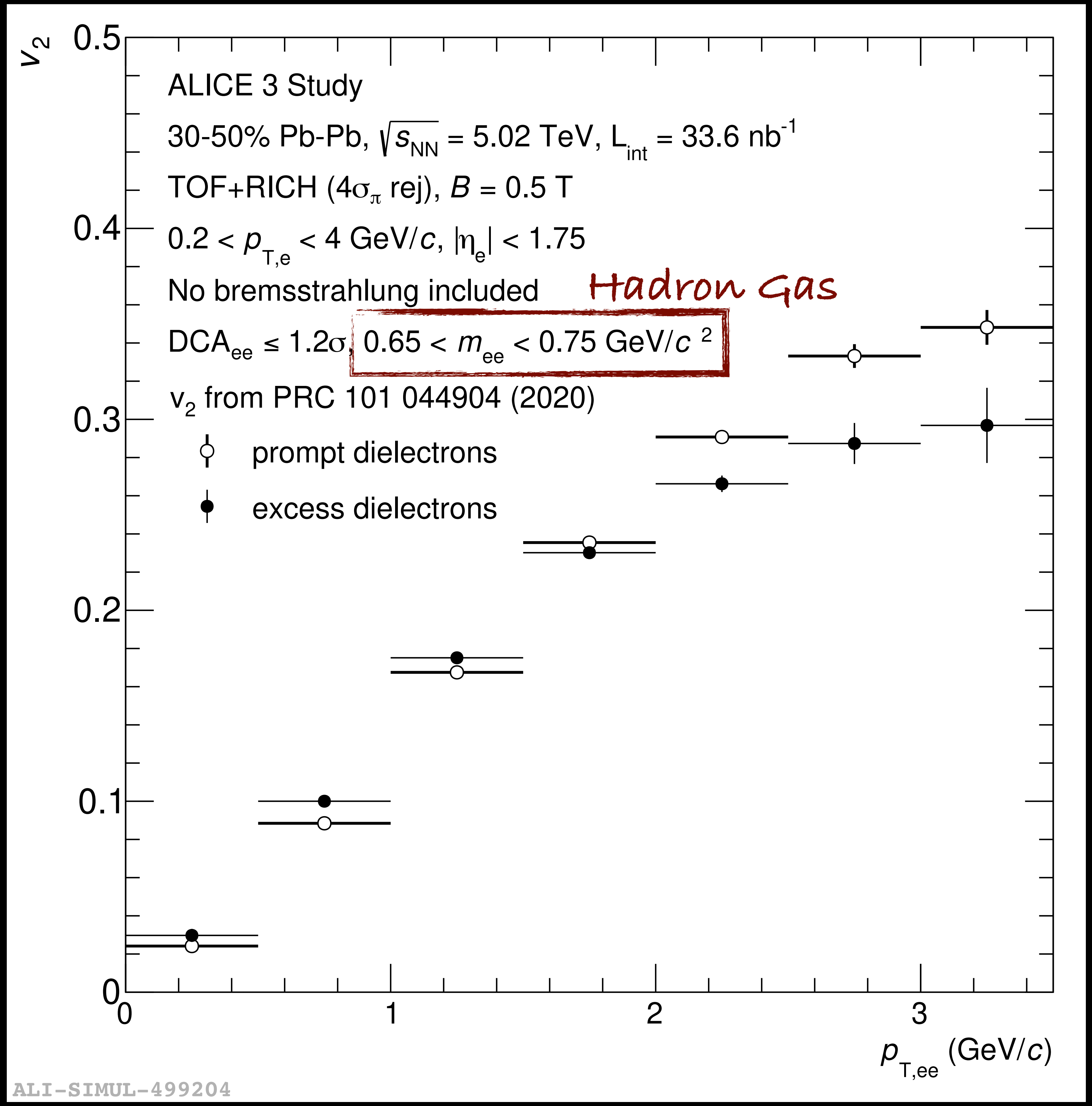
Integrated:
±1.5% stat. ±2% syst. uncertainty
(ITS 3: ±4% stat. $^{+4\%}_{-10\%}$ syst. uncertainty)

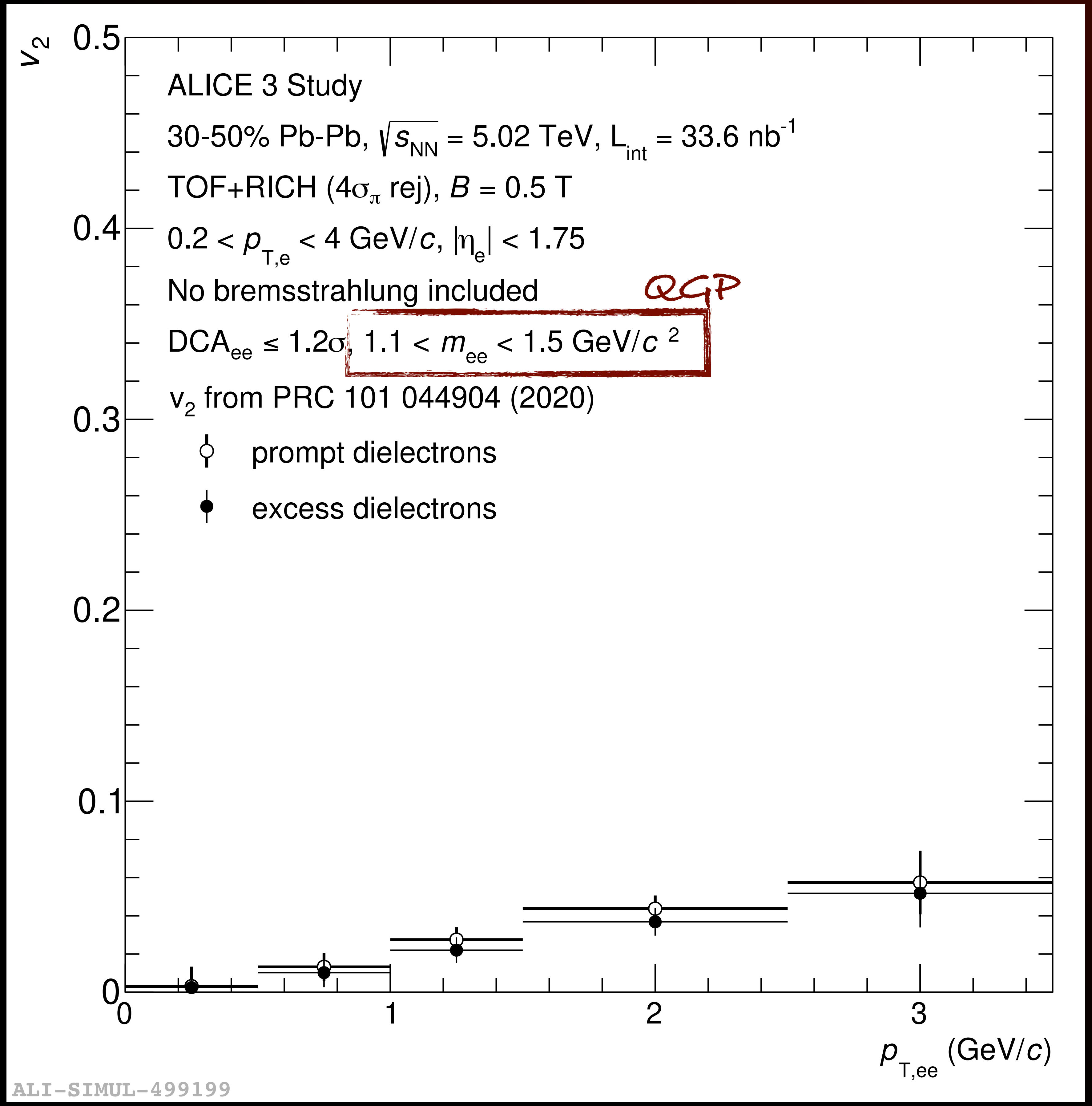
CERN-LHCC-2022-009



Elliptic flow

Projection for dielectron v_2 in mass regions with dominant thermal contributions





CERN-LHCC-2022-009

Statistical significant measurements possible

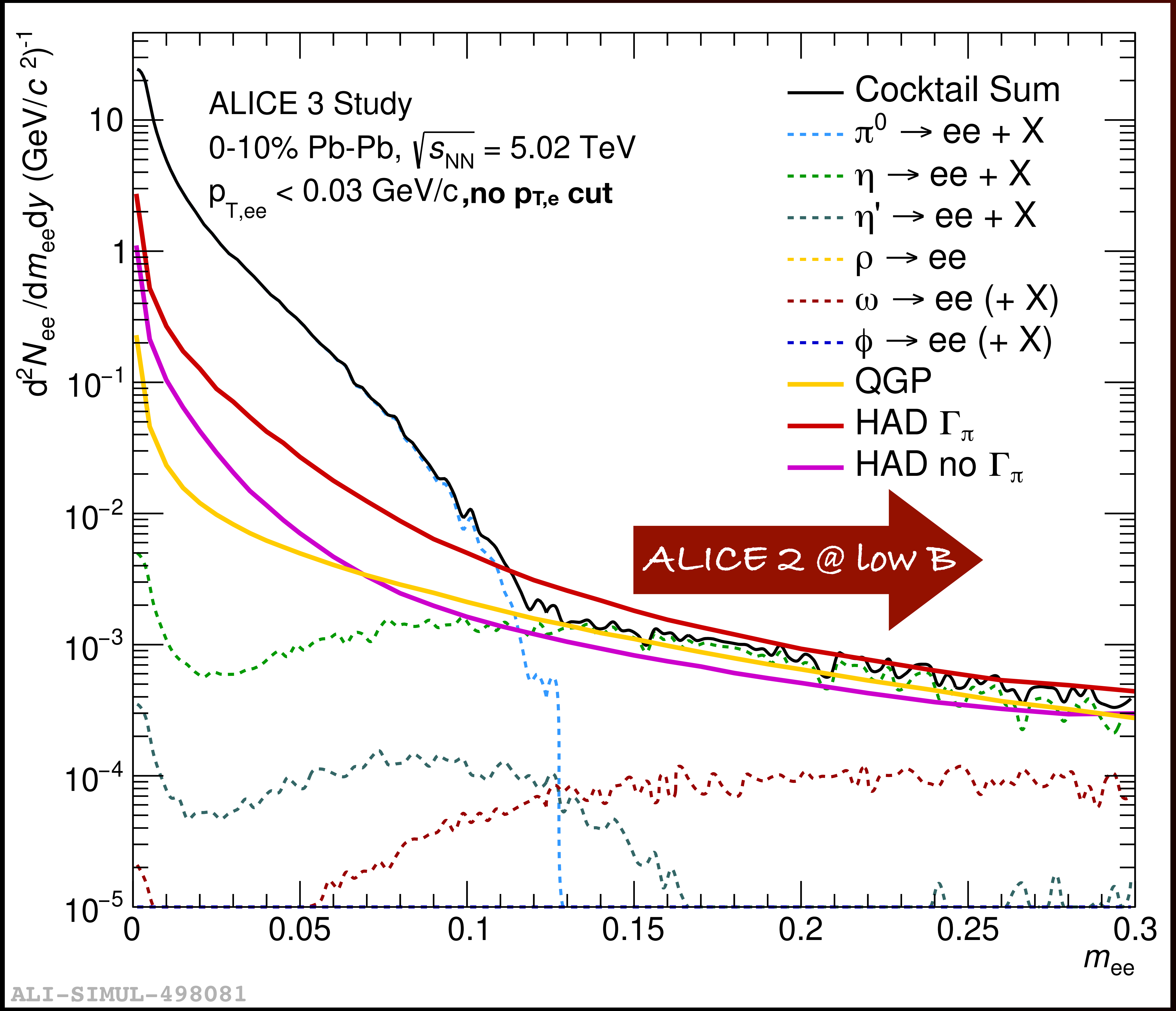
Electric conductivity

A first look

Very low pair p_T selection enhances thermal contributions wrt hadronic cocktail

Width of thermal contribution sensitive to electric conductivity

Acceptance at very low $p_{T,ee}$ and low m_{ee} needed



Crucial: precise measurement of η (π^0) to smallest p_T

What are other backgrounds?

η meson acceptance

Mid rapidity:

- Photons are required to have p_T > 0.1 GeV/c

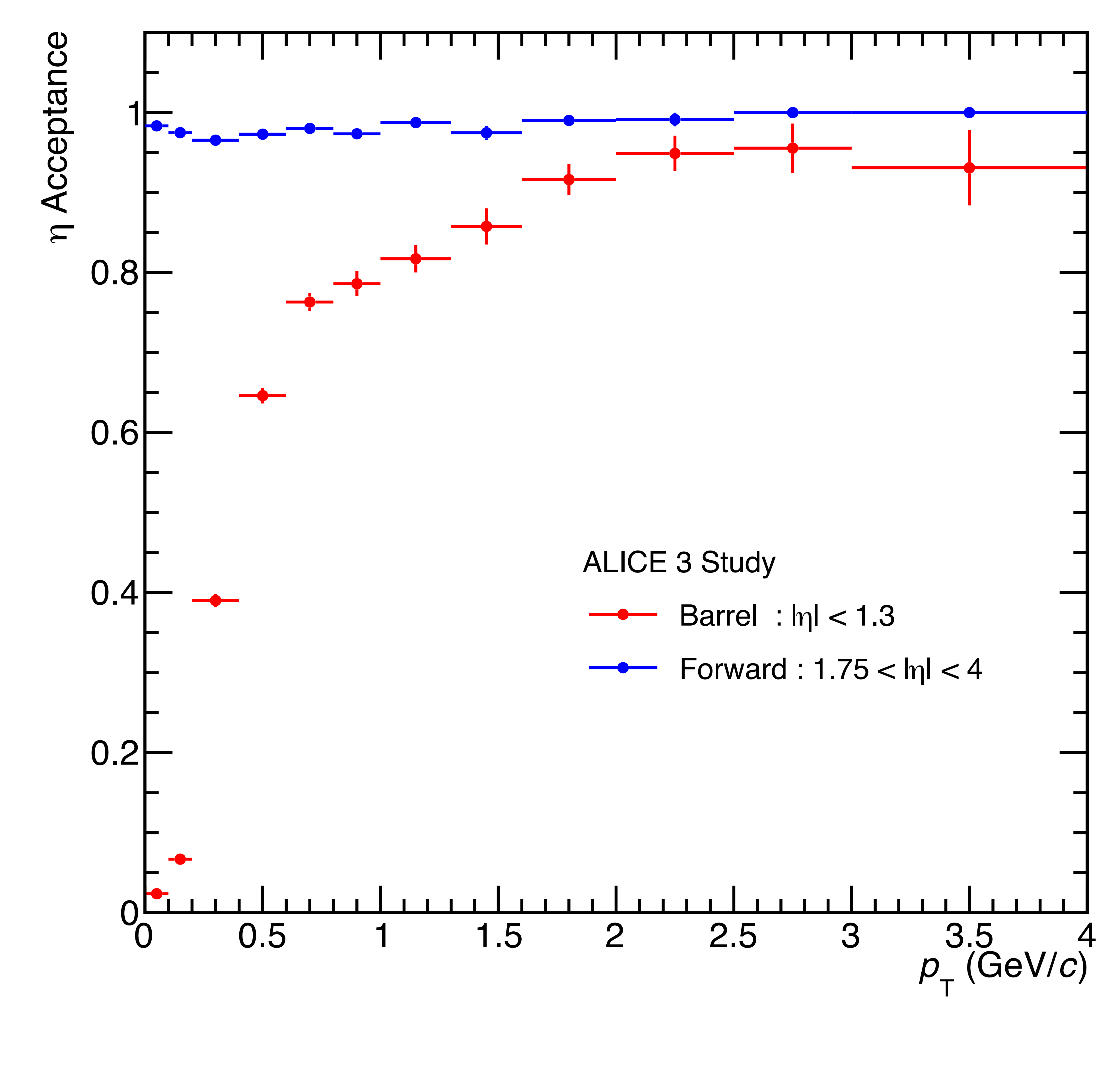
Limited to low p_T

Forward:

- Photon p > 0.1 Gev/c

No limitation at low p_T

Drastic reduction of uncertainties of direct photon measurements expected



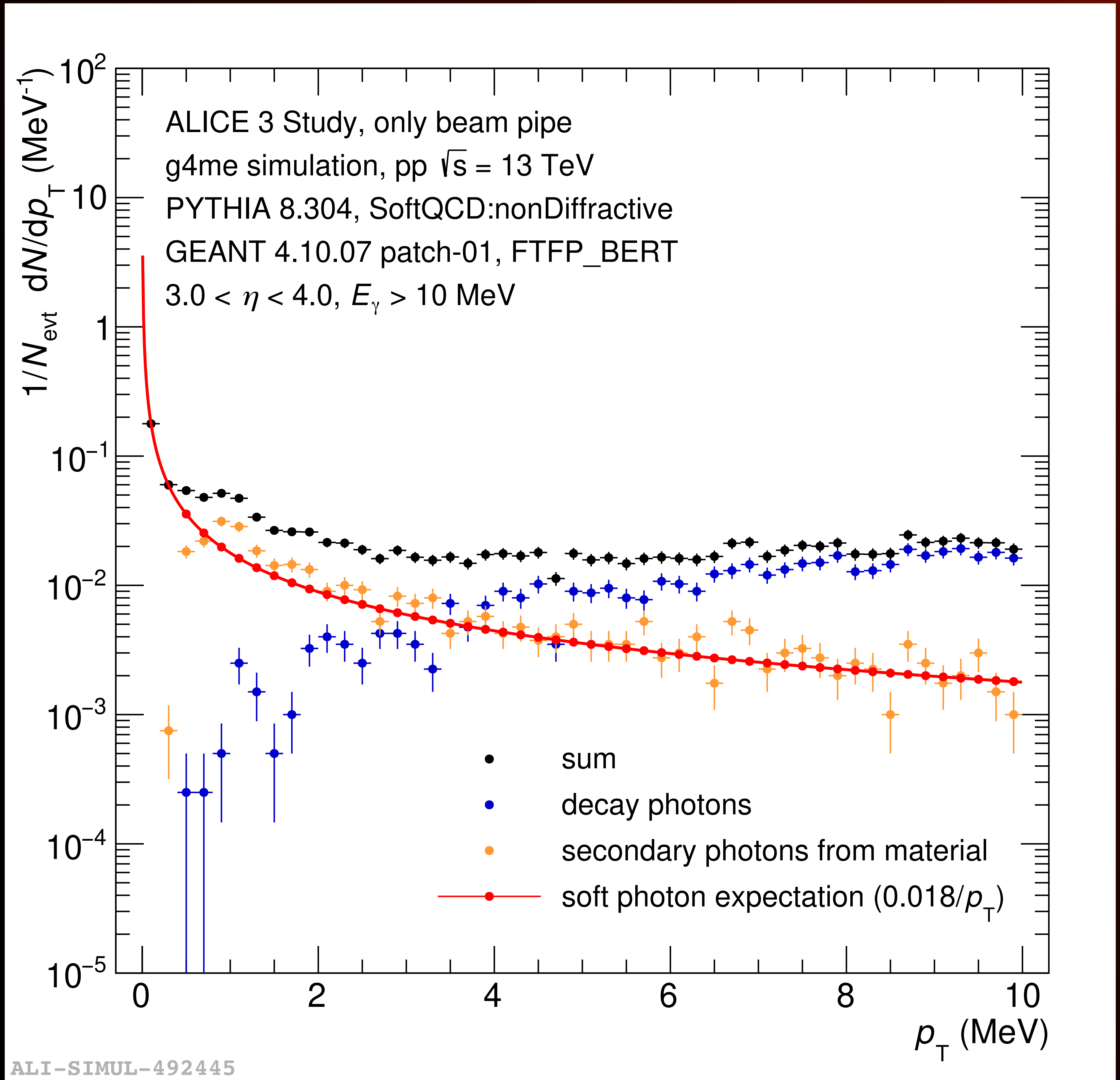
Soft photons

Signal and Background

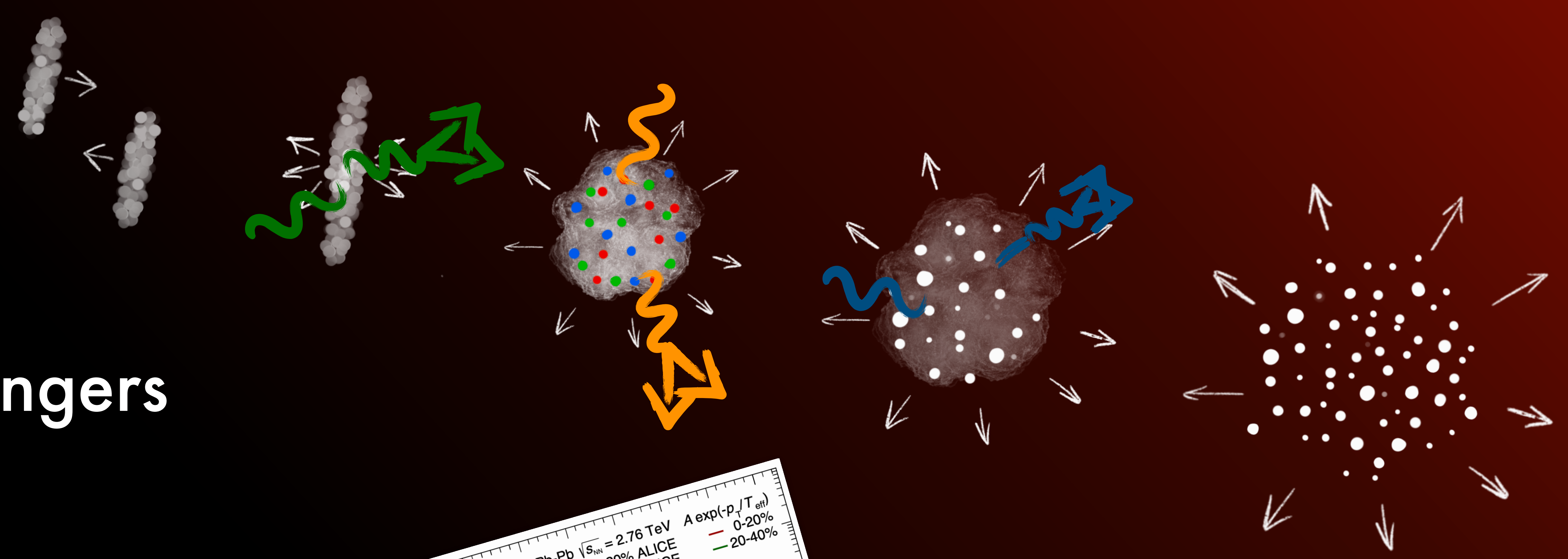
At low p_T bremsstrahlung dominant over decay photons

Electron veto reduces contribution from material

Additional modification of beam pipe possible to reduce material contribution



Conclusion



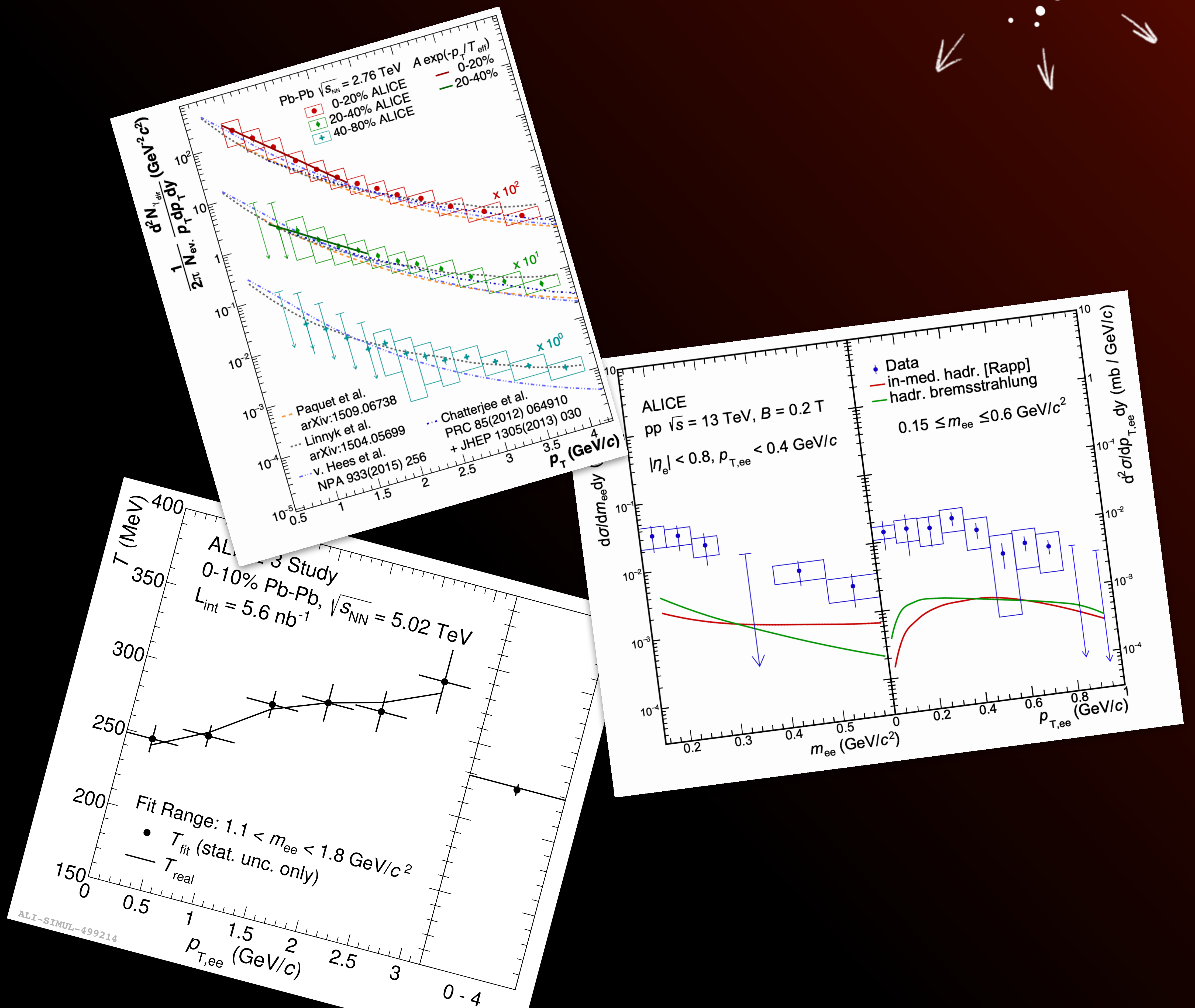
Electromagnetic probes are real multi messengers of heavy ion collisions

Measurements give constraints to modelling of the space time evolution of heavy ion collisions

- Necessary to disentangle different sources of EM probes

Still open questions (direct photon puzzle, soft photons)

Compelling physics cases to continue measurements of EM probes



Backup

ALICE 3

A selection of topics

Precision measurements of dileptons

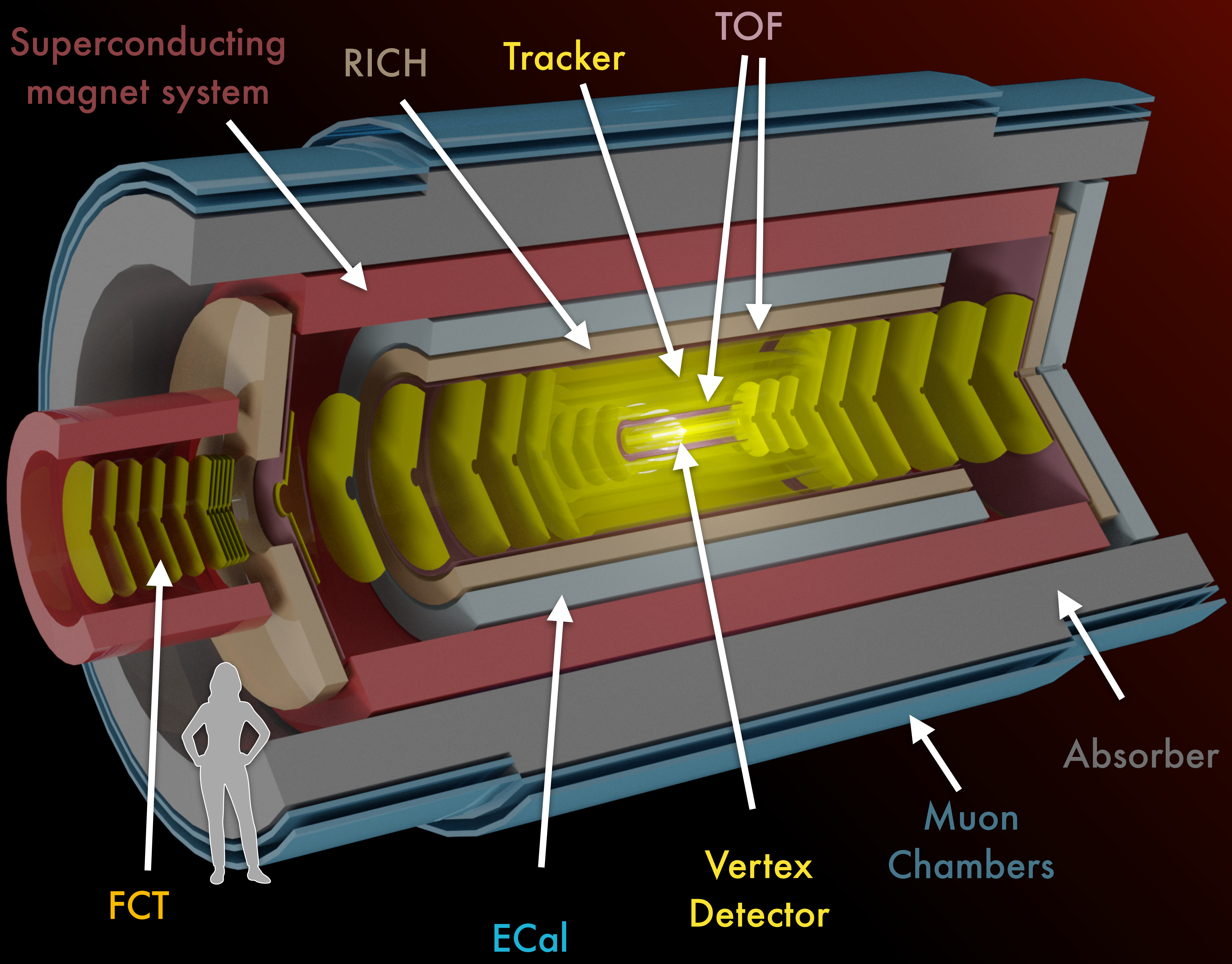
- ➟ mechanisms of chiral symmetry restoration in the quark-gluon plasma
- ➟ evolution of the quark-gluon plasma

Systematic measurements of (multi-)heavy-flavour hadrons

- ➟ transport properties in the quark-gluon plasma
- ➟ mechanisms of hadronisation from the quark-gluon plasma

Hadron correlations

Super Soft Photon Conversions



Soft photons

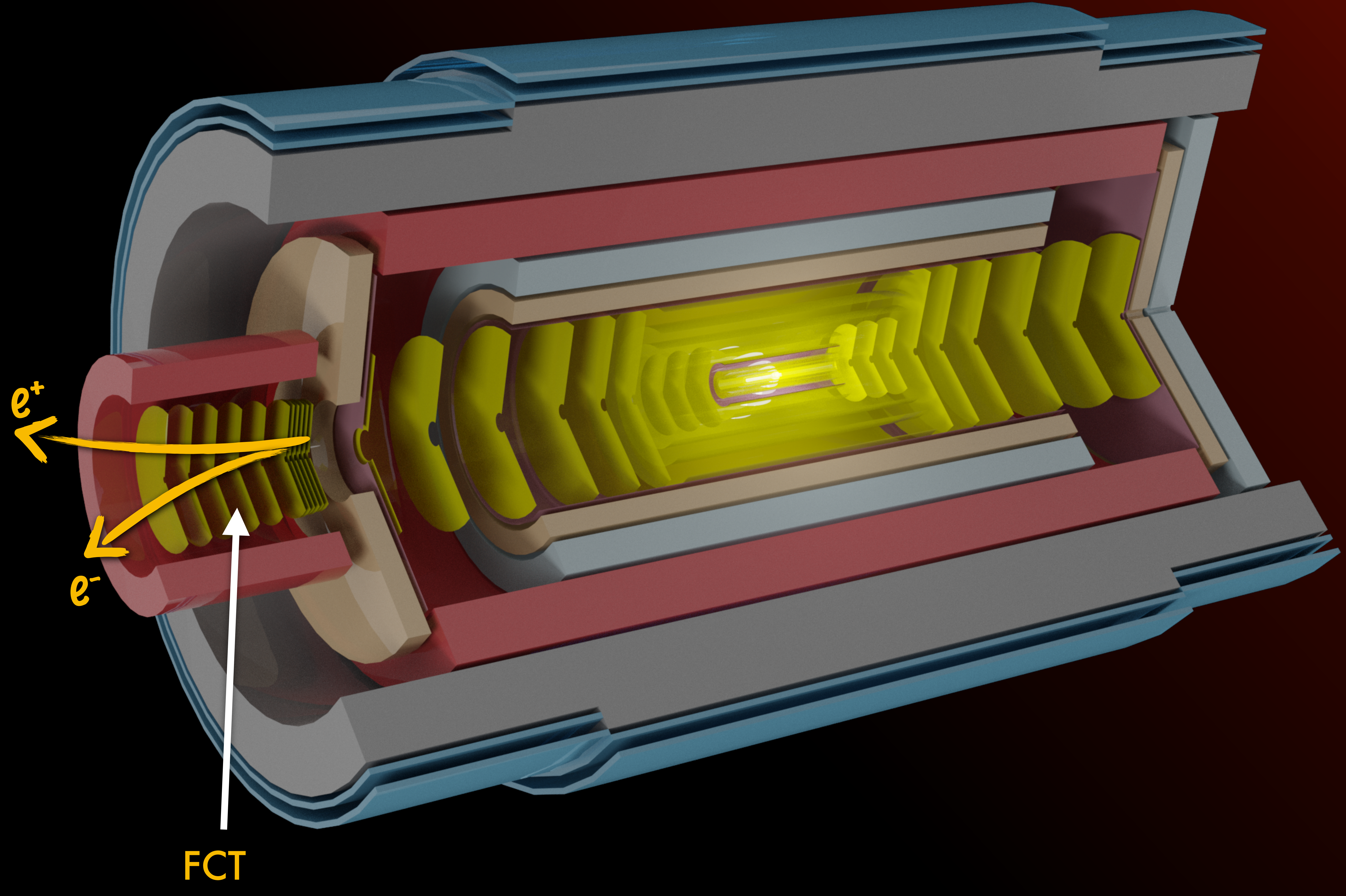
Motivation

At very low p_T: γ produced mainly via inner Bremsstrahlung

Can be calculated via Low theorem if in- and out-going particles can be measured

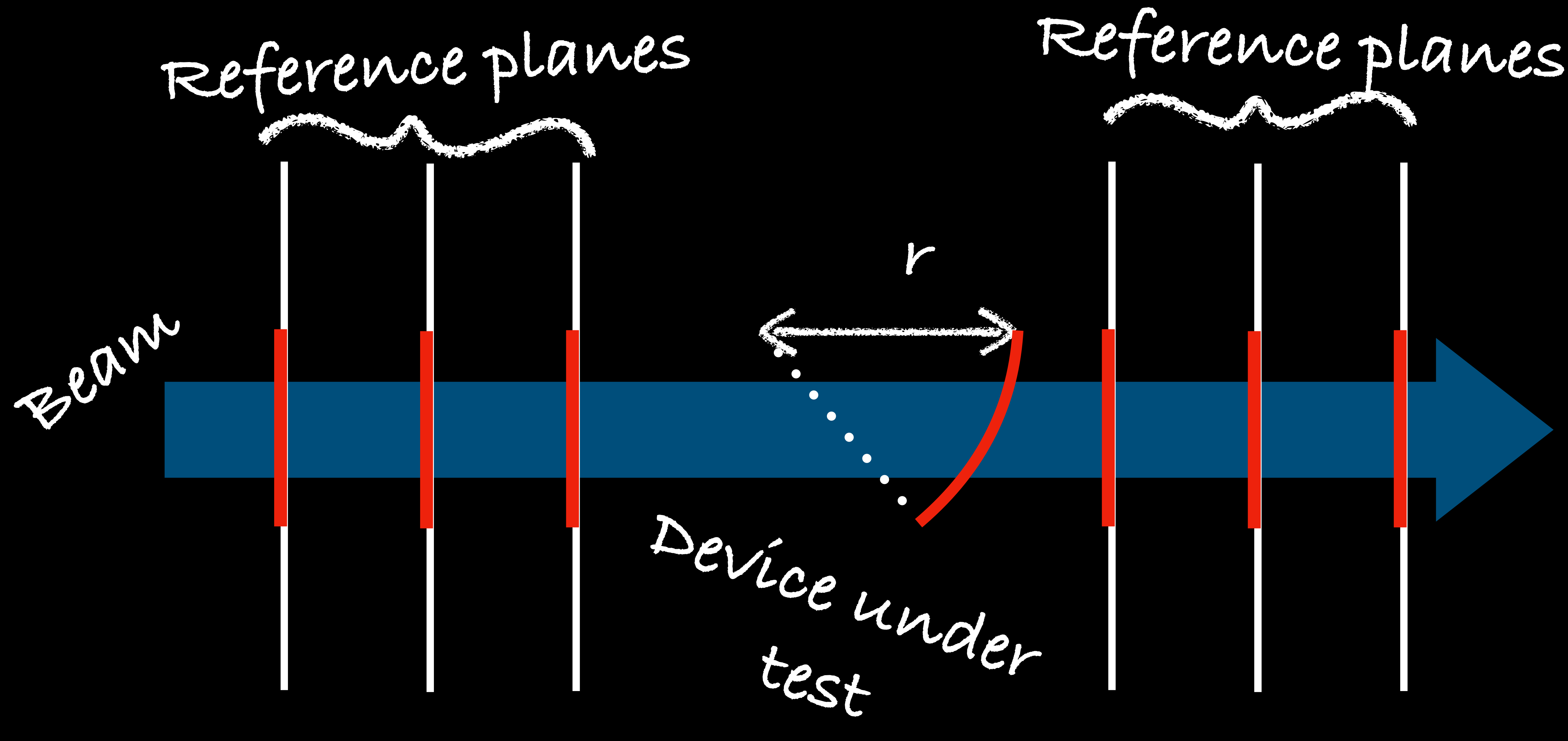
Previous measurements:
Factor 5 difference
→ no discrepancies seen in ee→μμγ

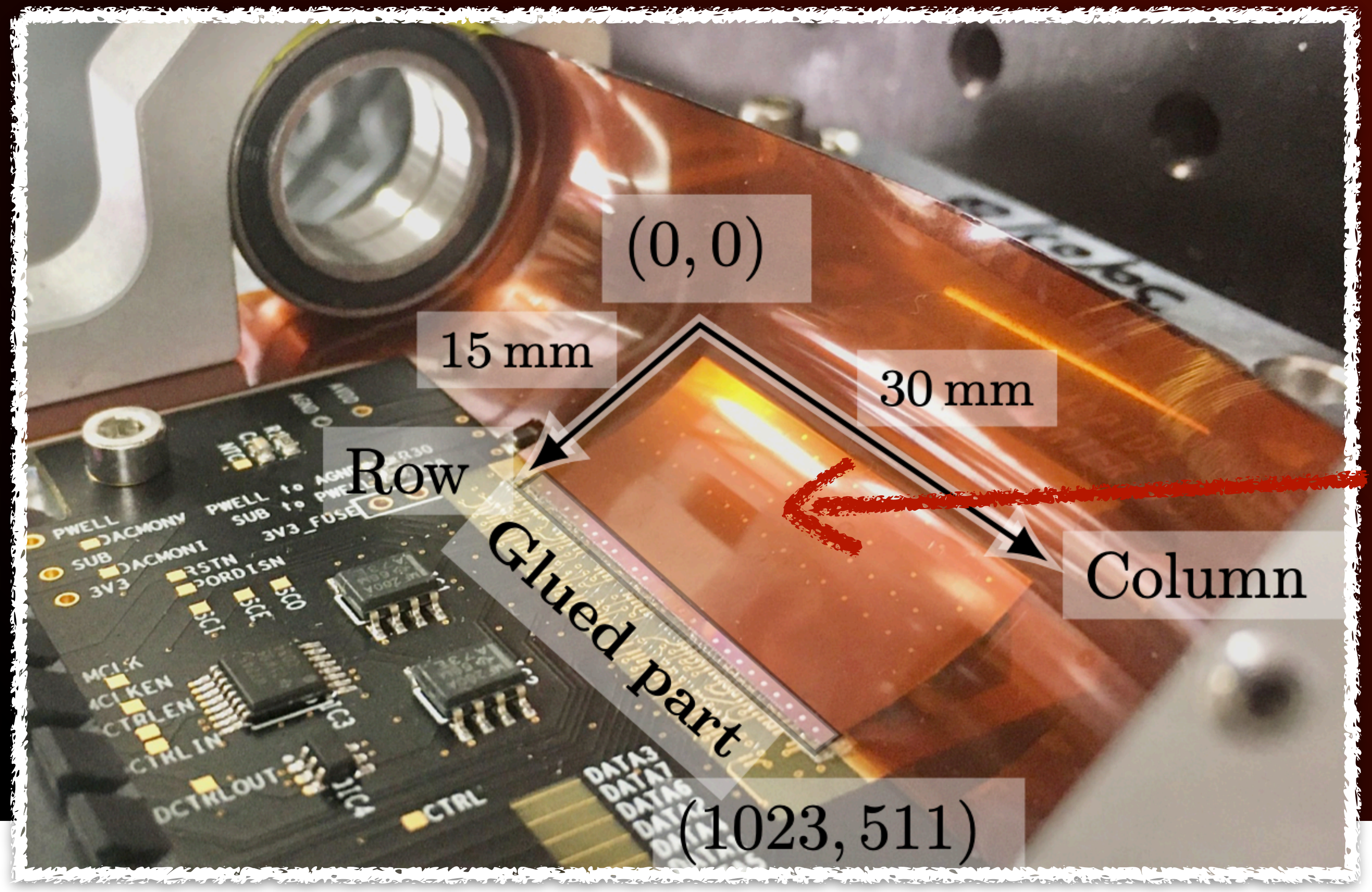
To measure lowest p_T → measure in forward direction



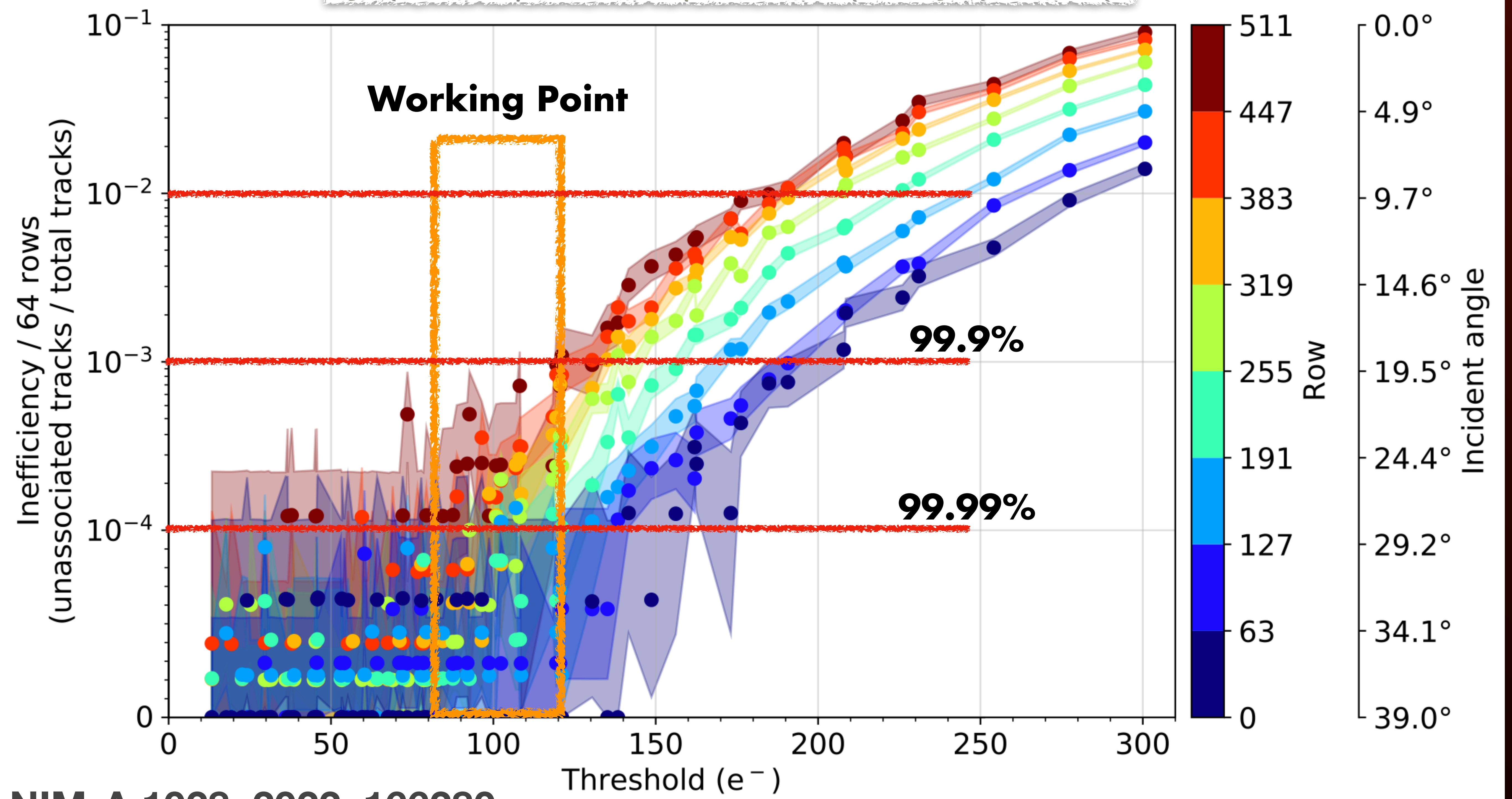
ITS3

Use ALPIDE telescope to test different devices:





Bent ALPIDE

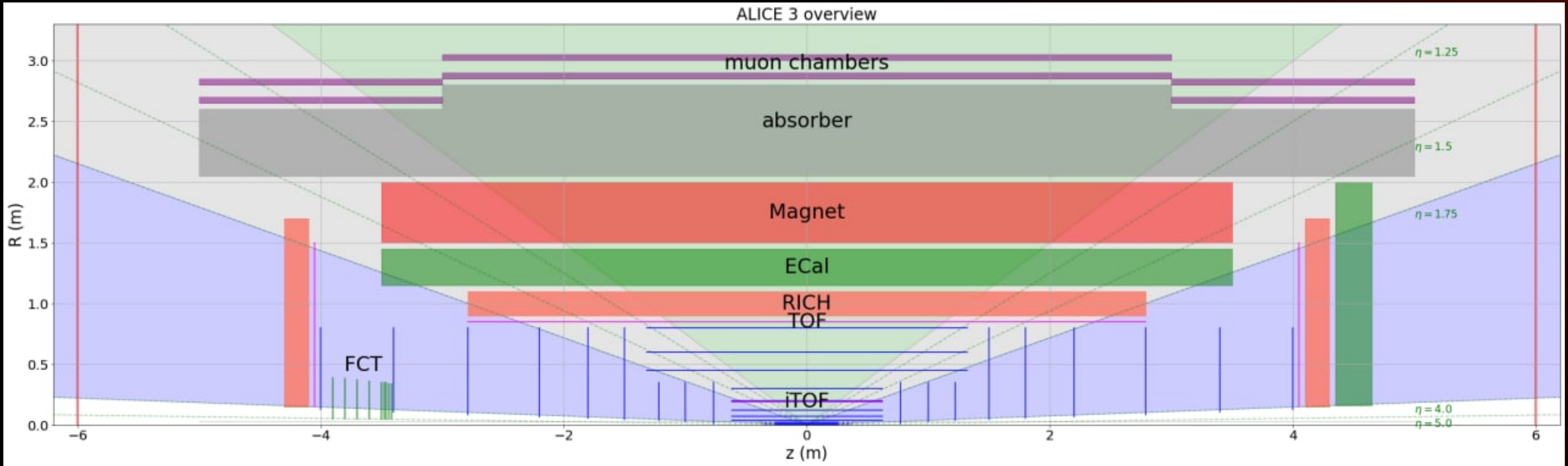


NIM-A 1028, 2022, 166280

Bent ALPIDE (180nm) efficiency > 99.9%

Digital pixel test structure (65 nm) efficiency > 99 %

A possible ALICE 3 setup



ALICE 3

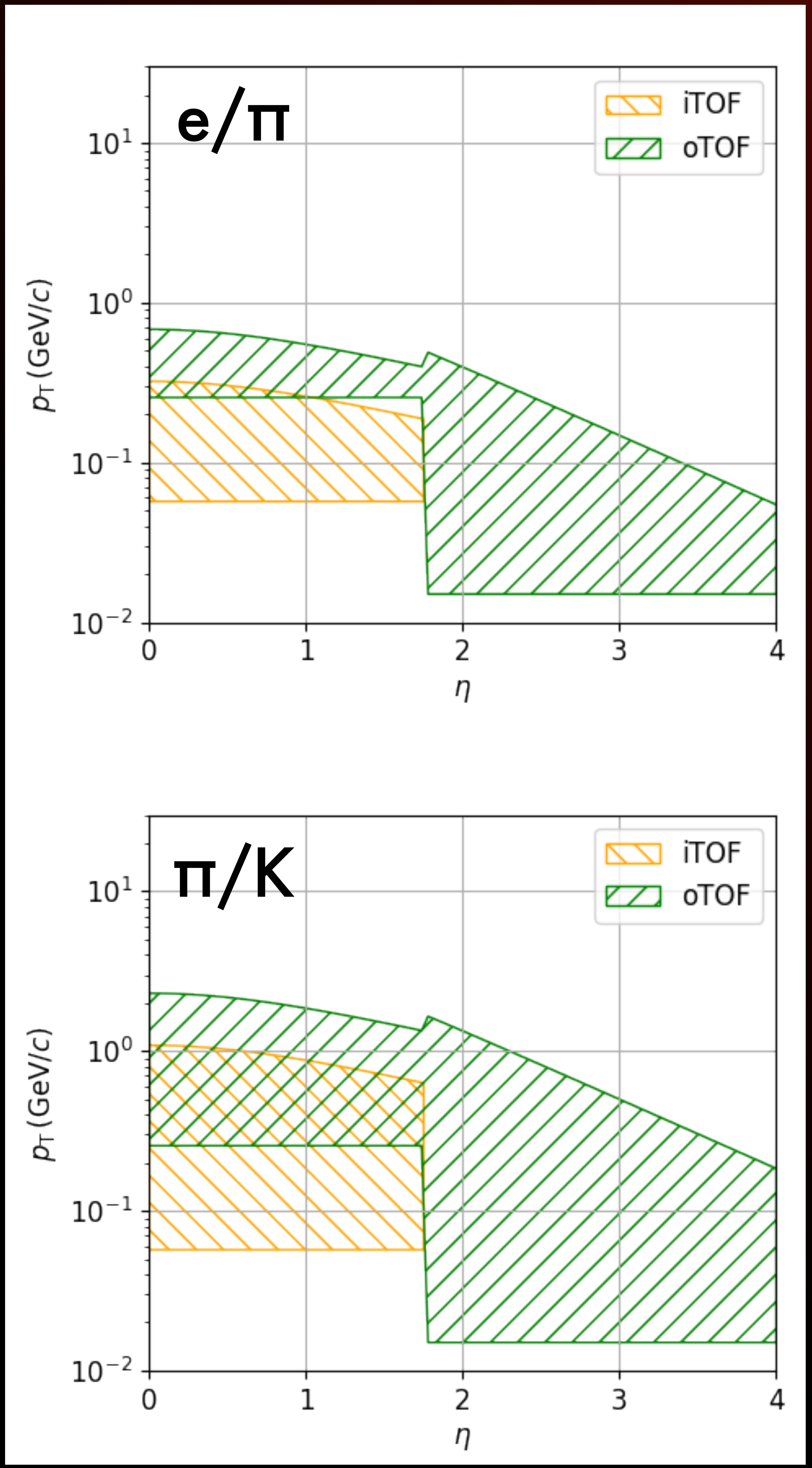
Particle identification TOF

Separation power $\propto \dfrac{L}{\sigma_{\text{tof}}}$

- distance and time resolution crucial
- larger radius results in lower p_T bound

- **2 barrel + 1 forward TOF layers**
  - outer TOF at R ≈ 85 cm
  - inner TOF at R ≈ 19 cm
  - forward TOF at z ≈ 405 cm

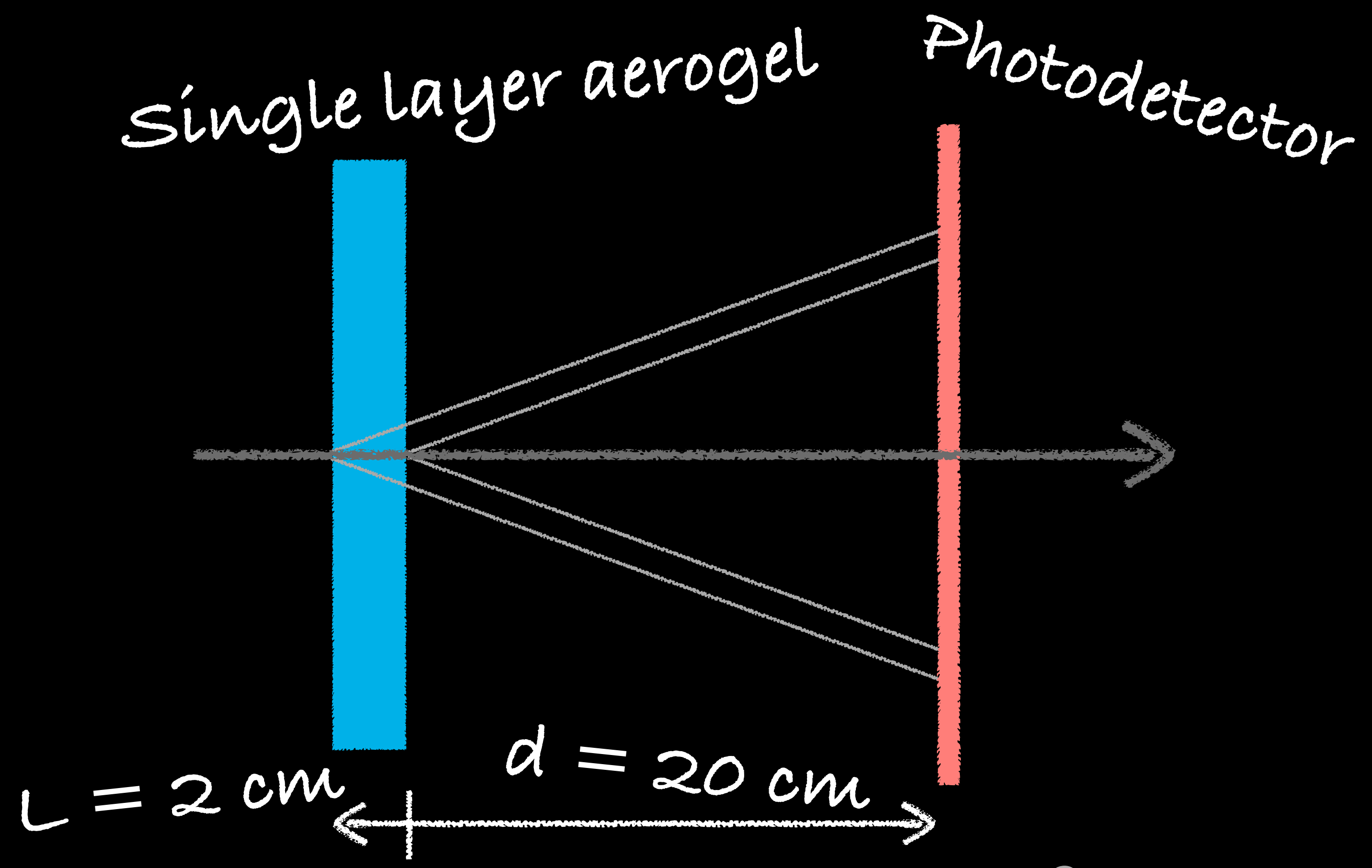
- **Silicon timing sensors** (σ_{TOF} ≈ 20 ps)

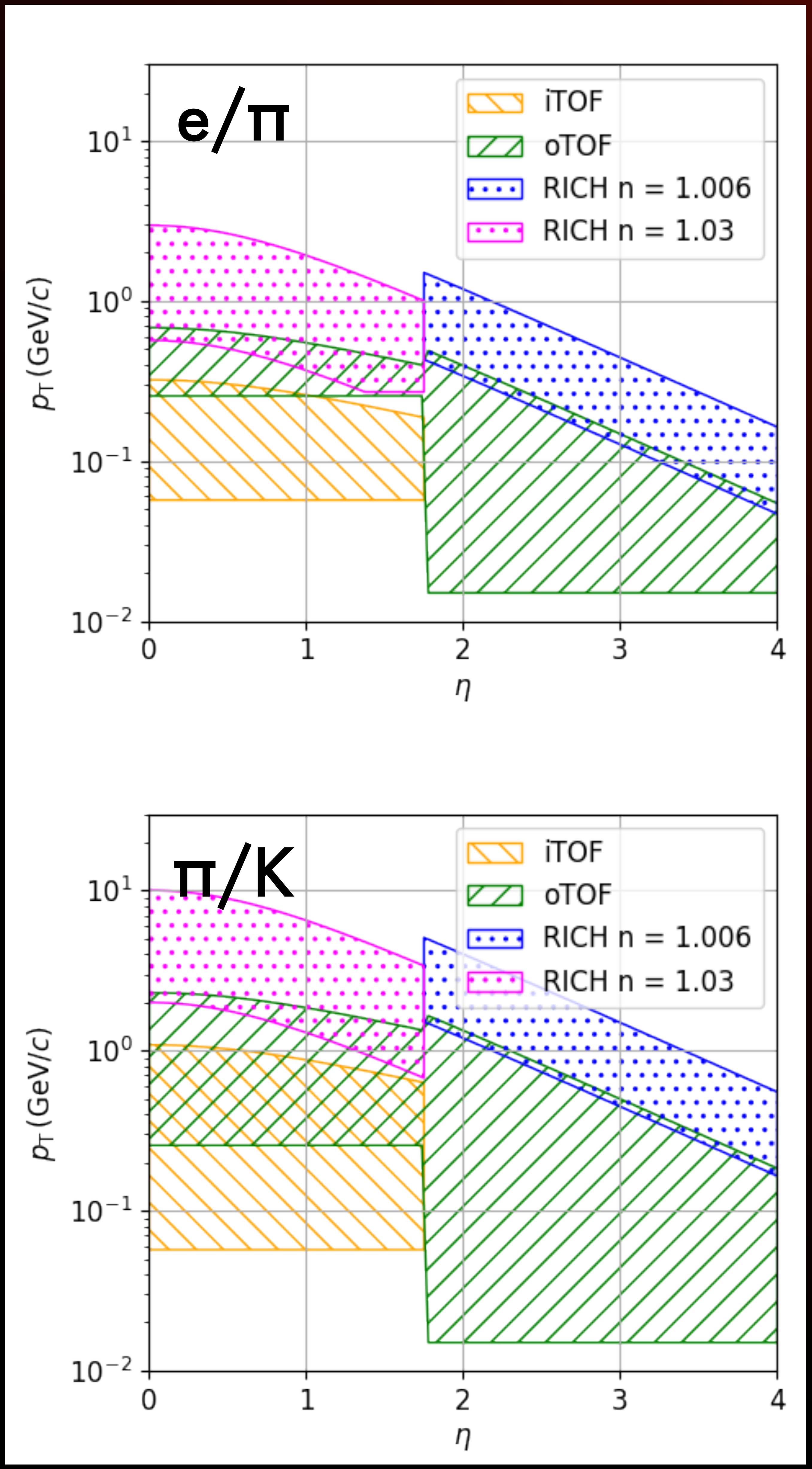


ALICE 3

Particle identification

- **Extend PID reach of outer TOF to higher p_T with Cherenkov**
  - **aerogel radiator**
    to ensure continuous coverage from TOF
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)





Excess yield

Thermal spectrum from QGP and hadron gas after subtraction of hadronic components

Compared to different ρ spectral functions:

- Including ρ-a1 mixing (reference)
- Without mixing of ρ and a1
- Vacuum ρ spectral function

Dominated by systematic uncertainties

Precision of data sufficient to measure 15% effect in ρ–a₁ mixing region

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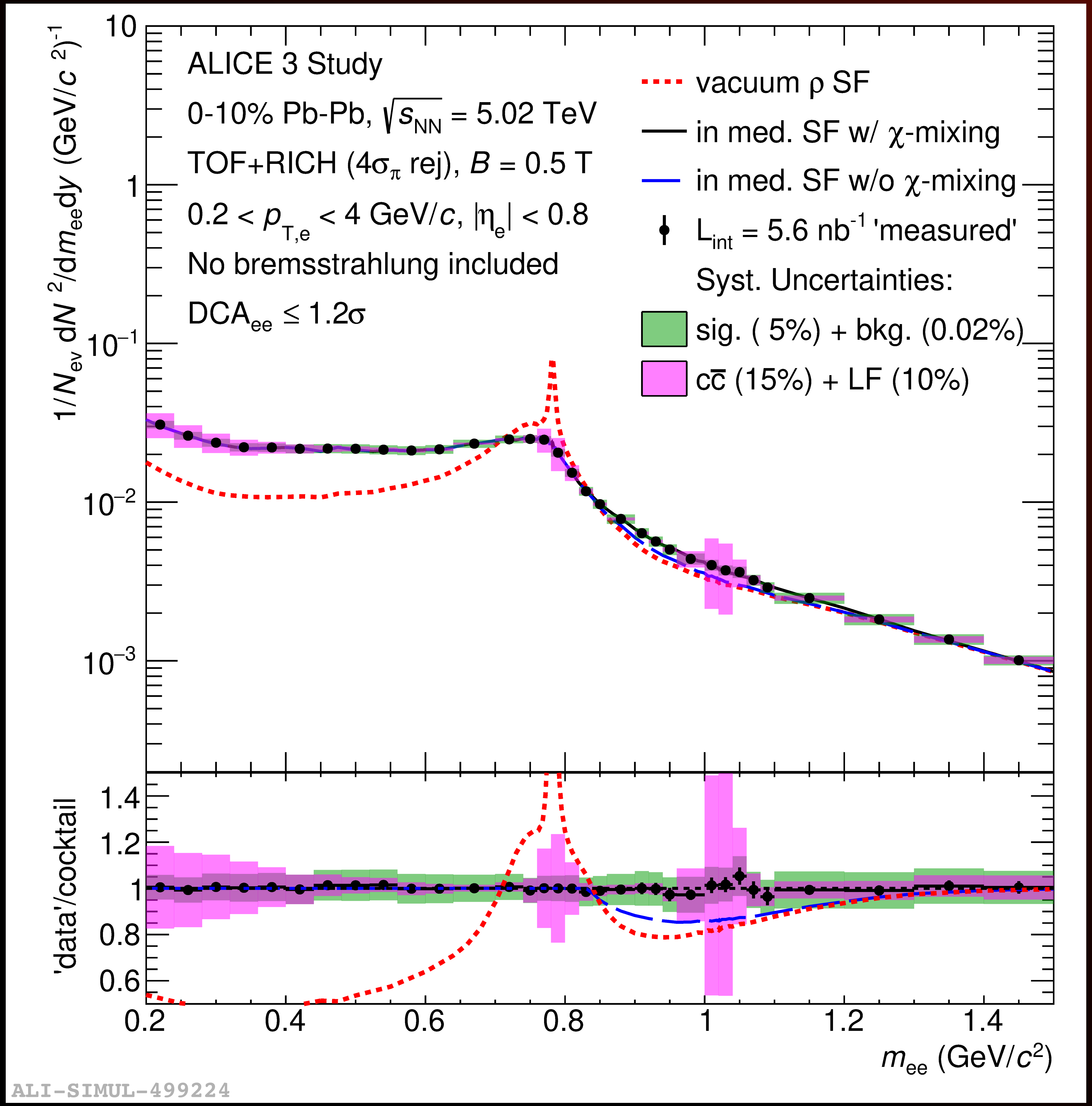
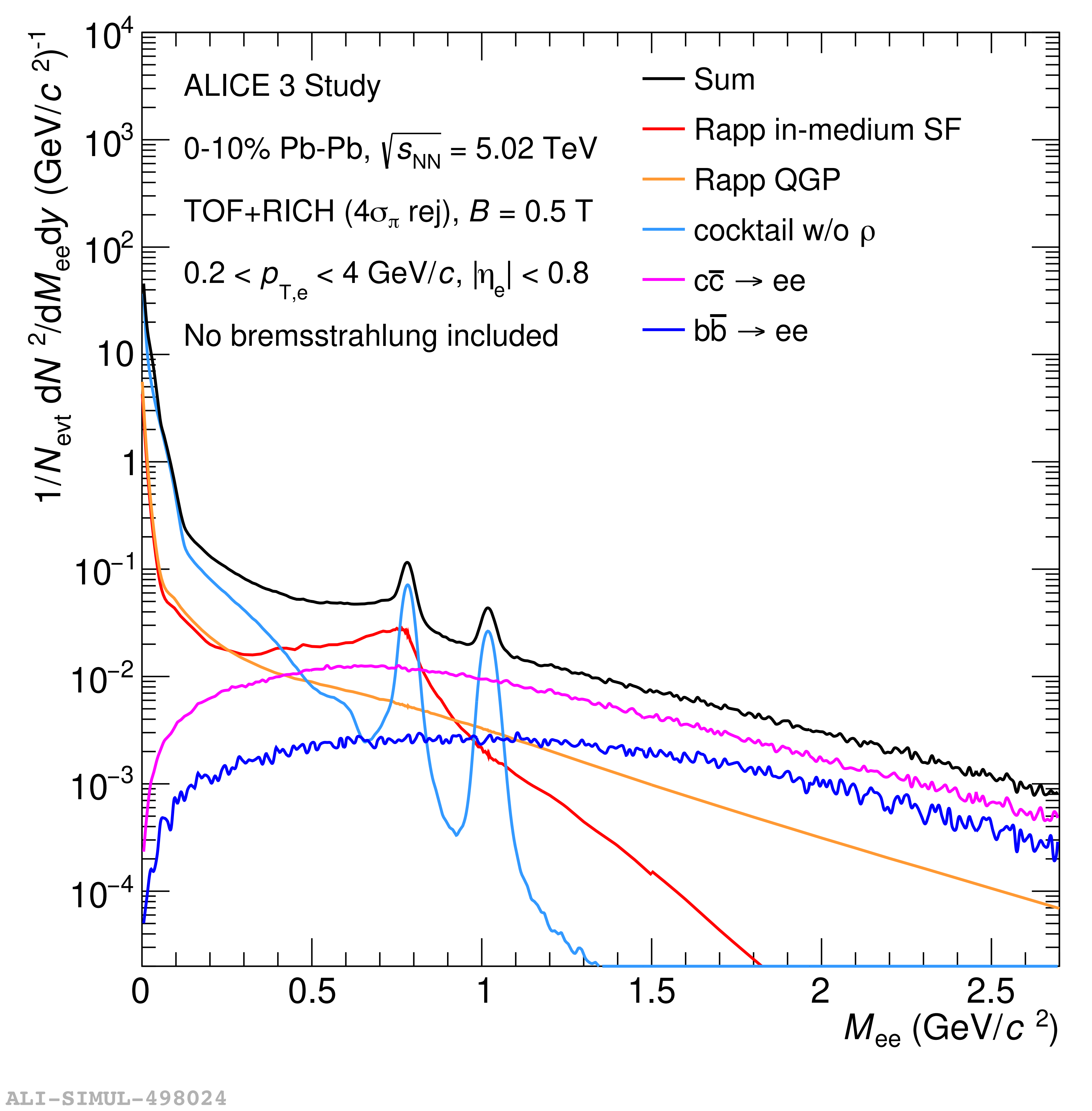


Dielectron cocktail

Cocktail ingredients:

- Light flavour:
  Measurements of particle spectra
- Correlated HF pairs:
  Measurement in pp + N_{coll} scaling + CNM (EPS09)
- Thermal radiation:
  Calculations by Ralf Rapp

Large charm contribution of wide mass range
→ dominant m_{ee} > 0.9 GeV/c²



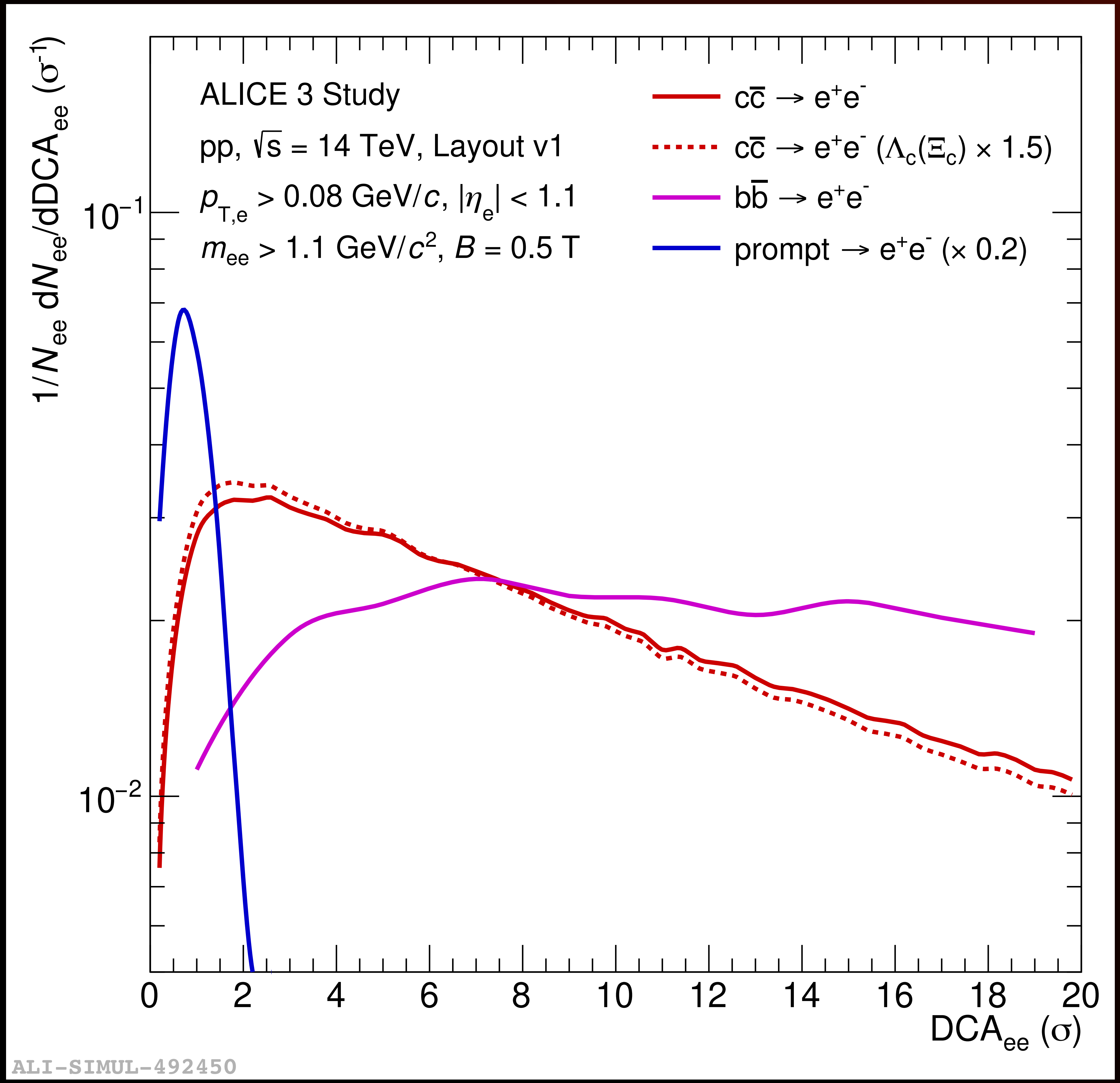
Distance of Closest Approach

DCA_{ee} templates for prompt, charm and beauty contributions

Ordering by decay length of mother particles as expected:

Prompt < Charm < Beauty

Changing hadron chemistry in the charm sector can change the shape of the template



Distance of Closest Approach

Charm hadron contributions

Sensitivity can be demonstrated on the level of different decay length of charm hadron species

cτ (Λ_c) = 60μm

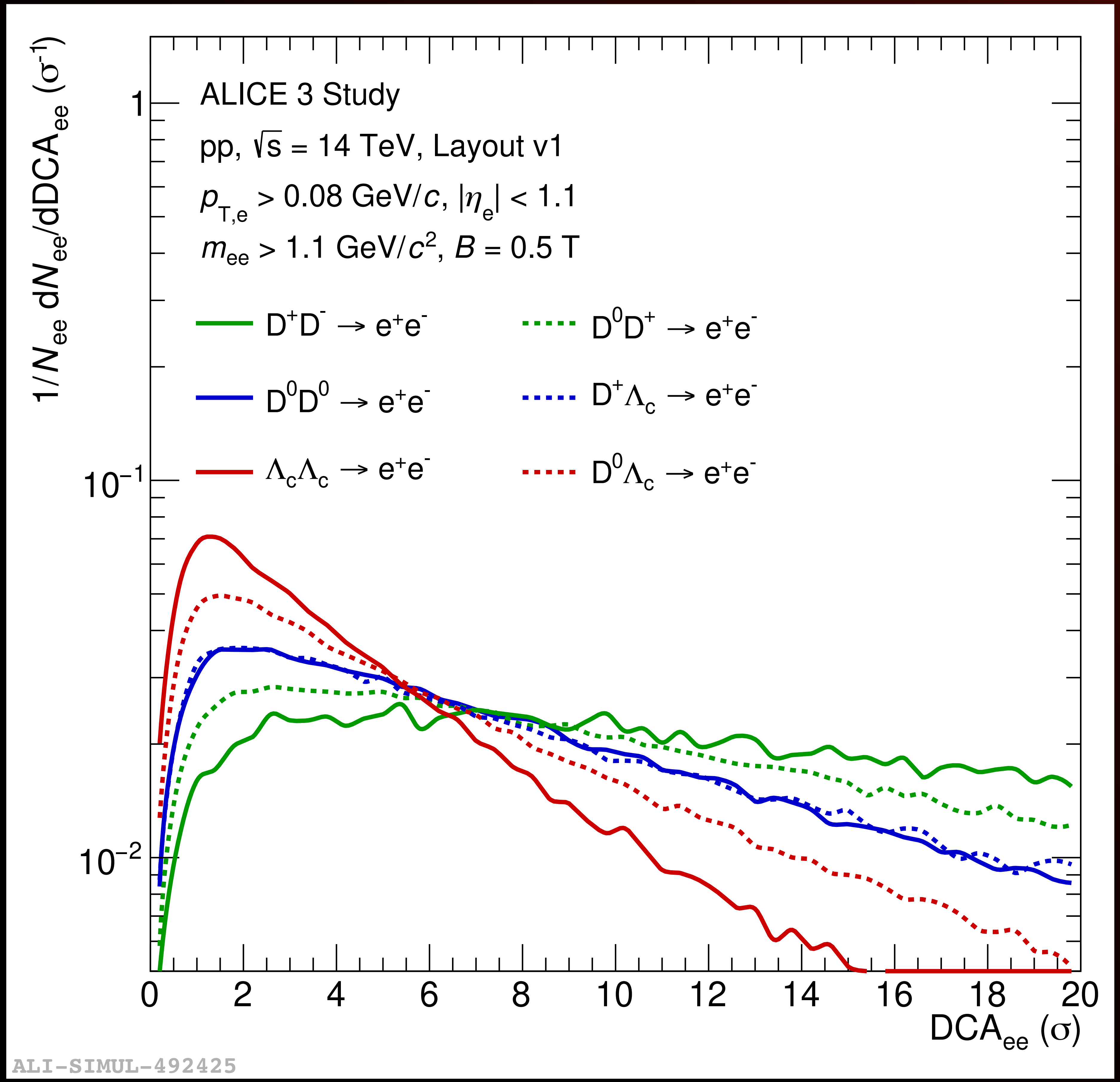
cτ (D^0) = 150 μm

cτ (D^+) = 300μm

Final template for charm from weighted sum of single contributions

Input are the measured branching ratios and fragmentation functions

Estimation of uncertainty underinvetigation



Distance of Closest Approach

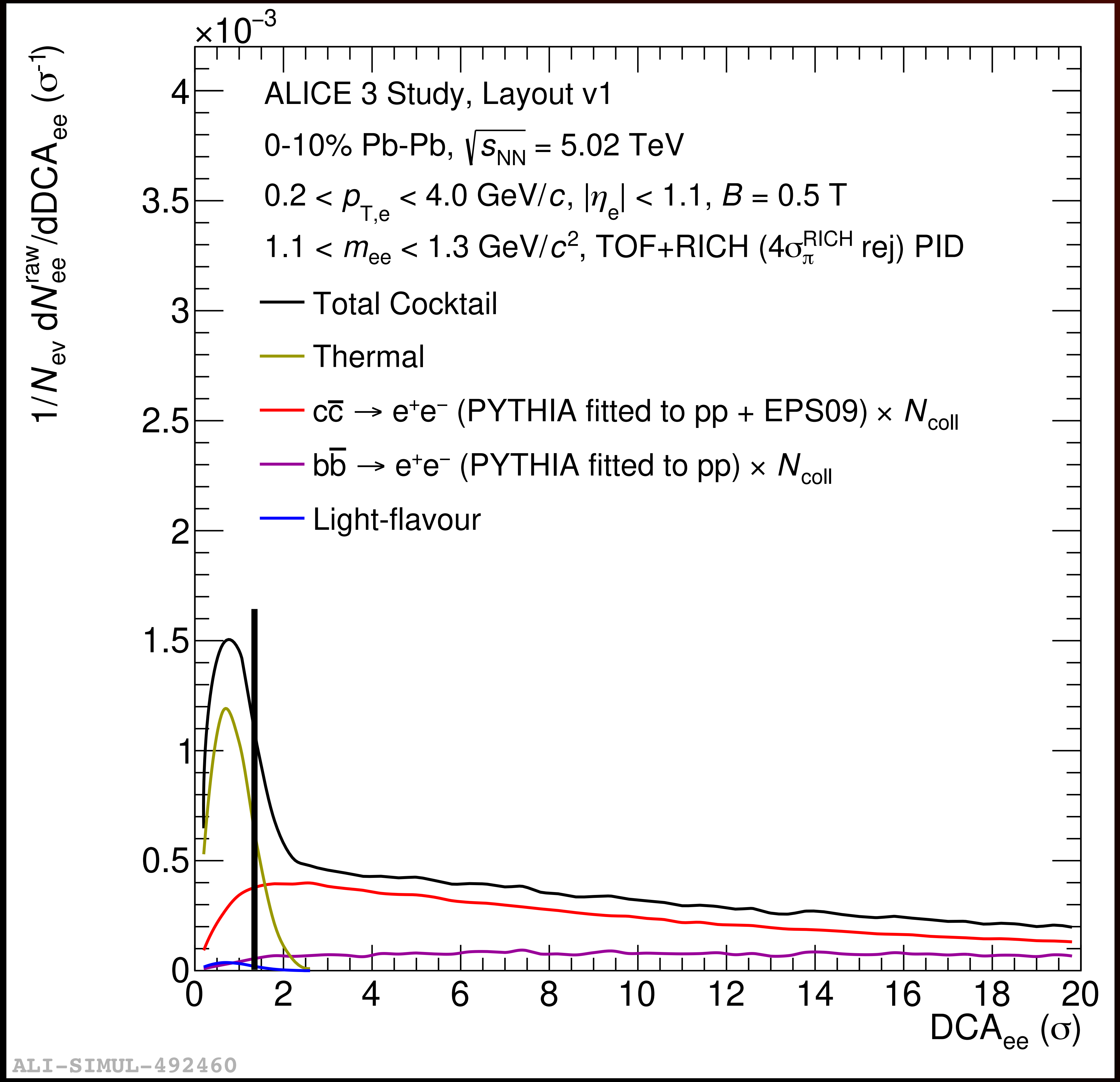
Expected raw DCA_{ee} contribution

Good separation of prompt and HF contributions

Selection at 1.2σ rejects:

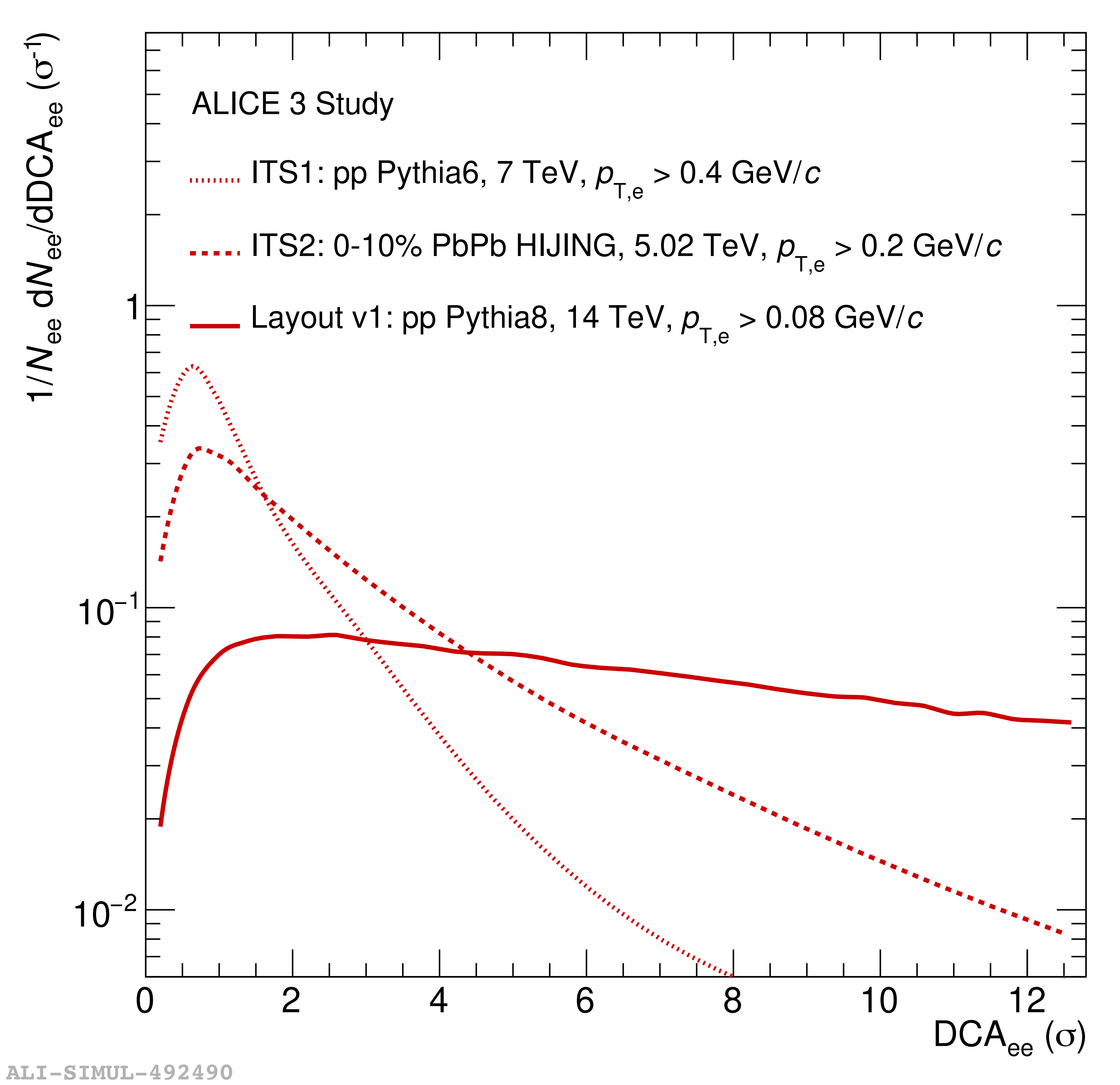
27% prompt, 94% charm, and 98% of beauty

ITS 3: 27% prompt, 83% charm



Distance of Closest Approach

Comparison with RUN1/3 performance



Elliptic flow

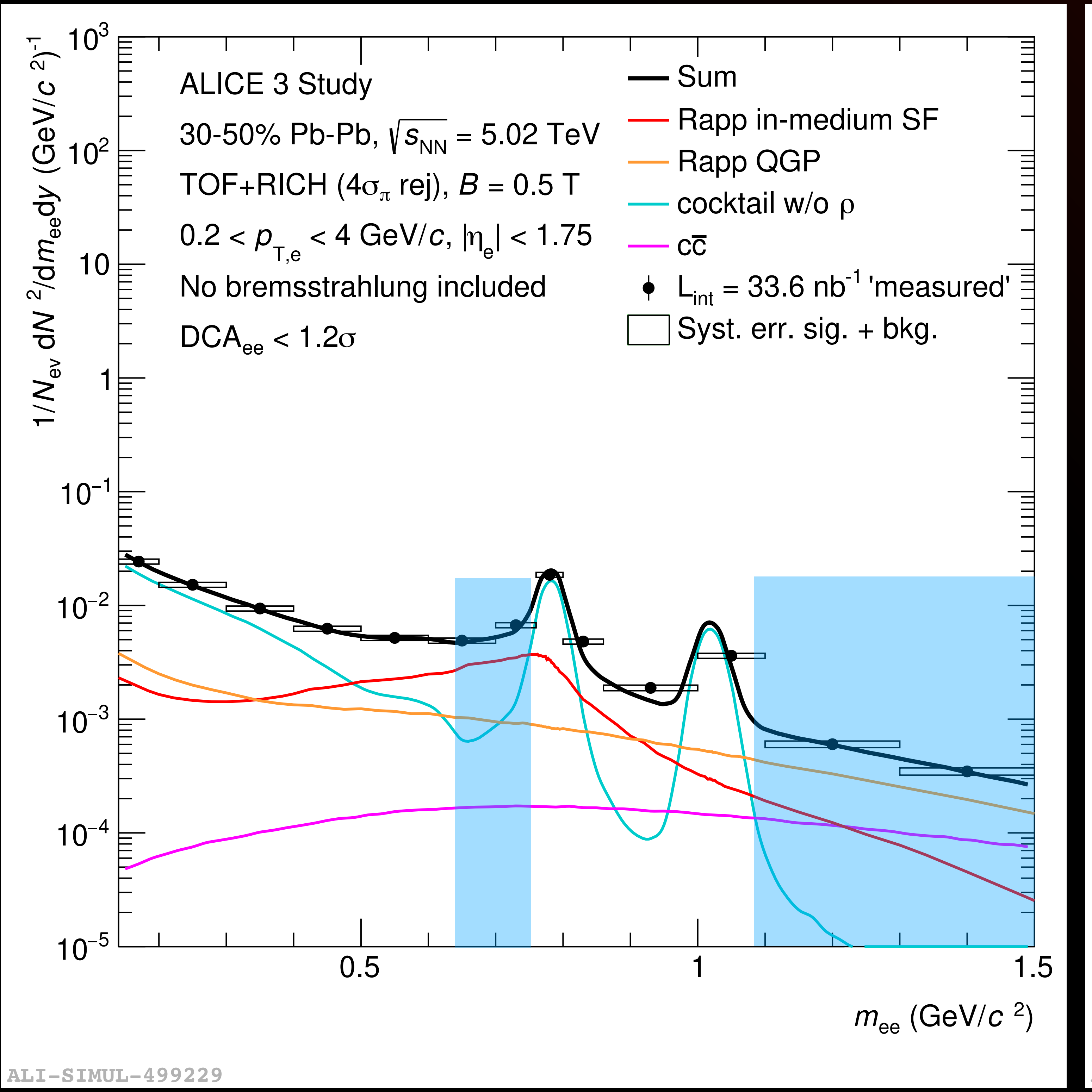
Yield and elliptic flow v_2 in semi-central (30–50%) Pb–Pb collisions for 6 years

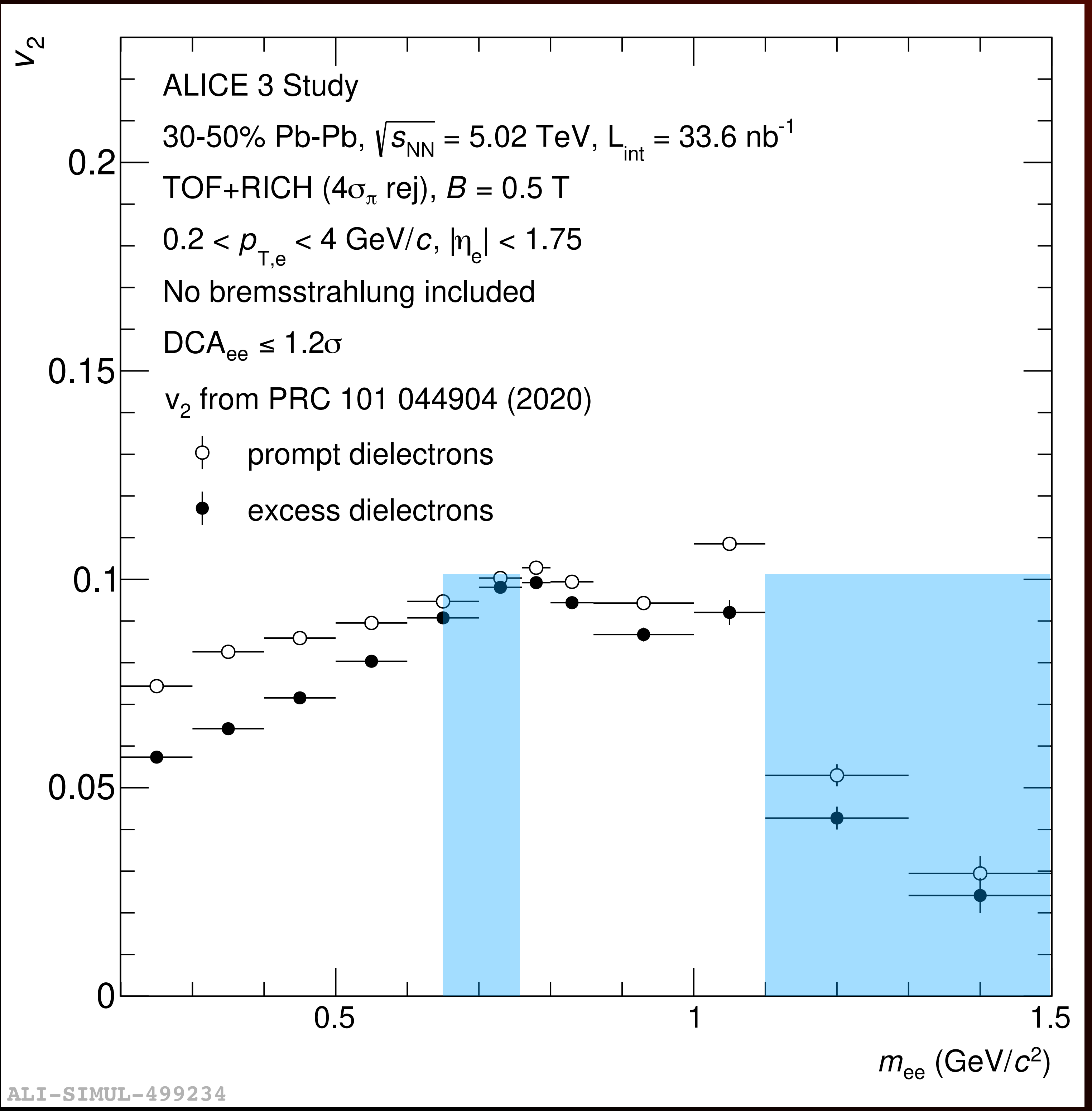
Important measurement together with photon v_2

Elliptic flow (hadronic and thermal) based on calculations by Gojko Vojanovic et al

Differential measurement statistical possible

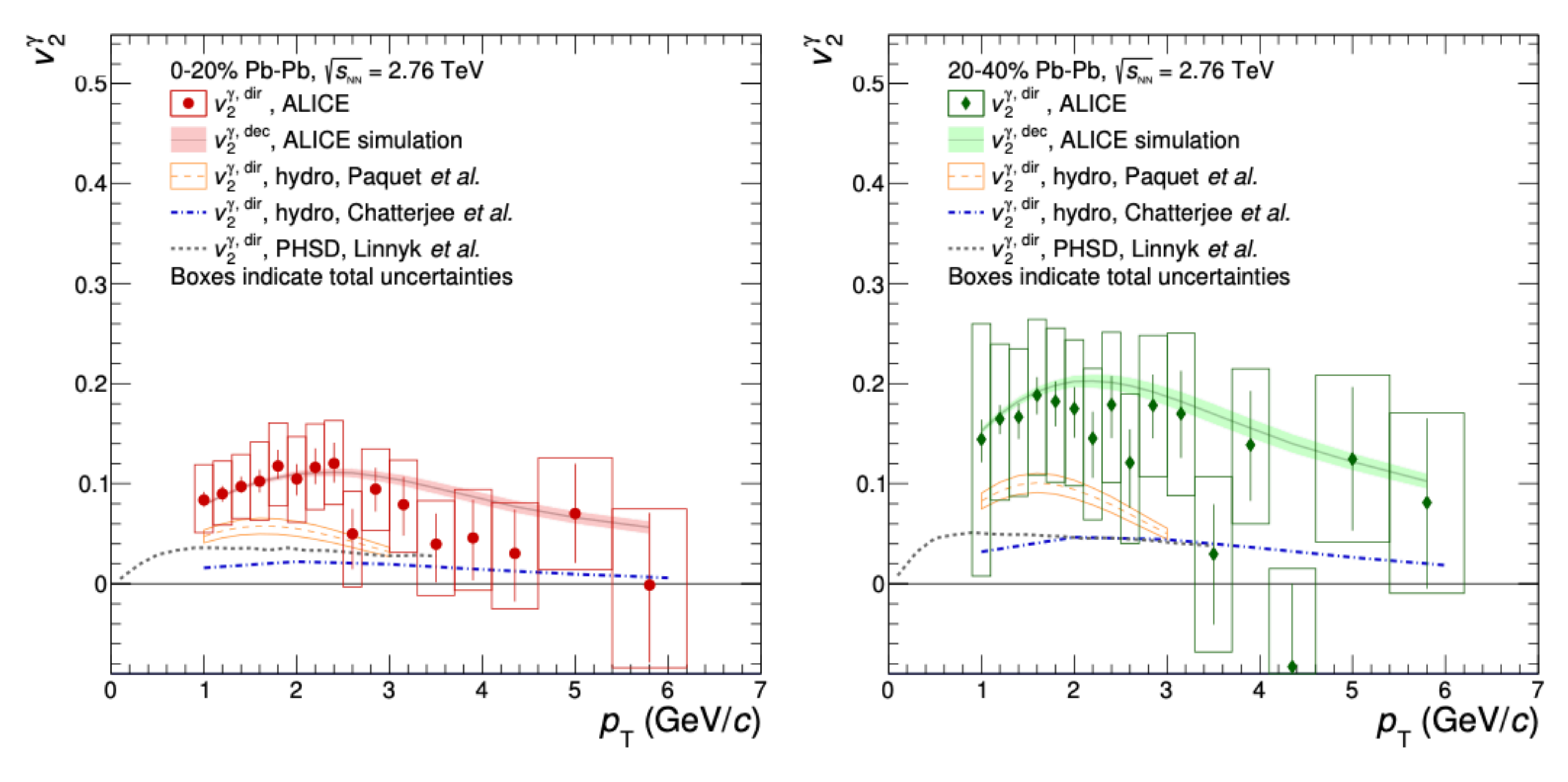
Look at regions with large contributions from hadron gas or QGP



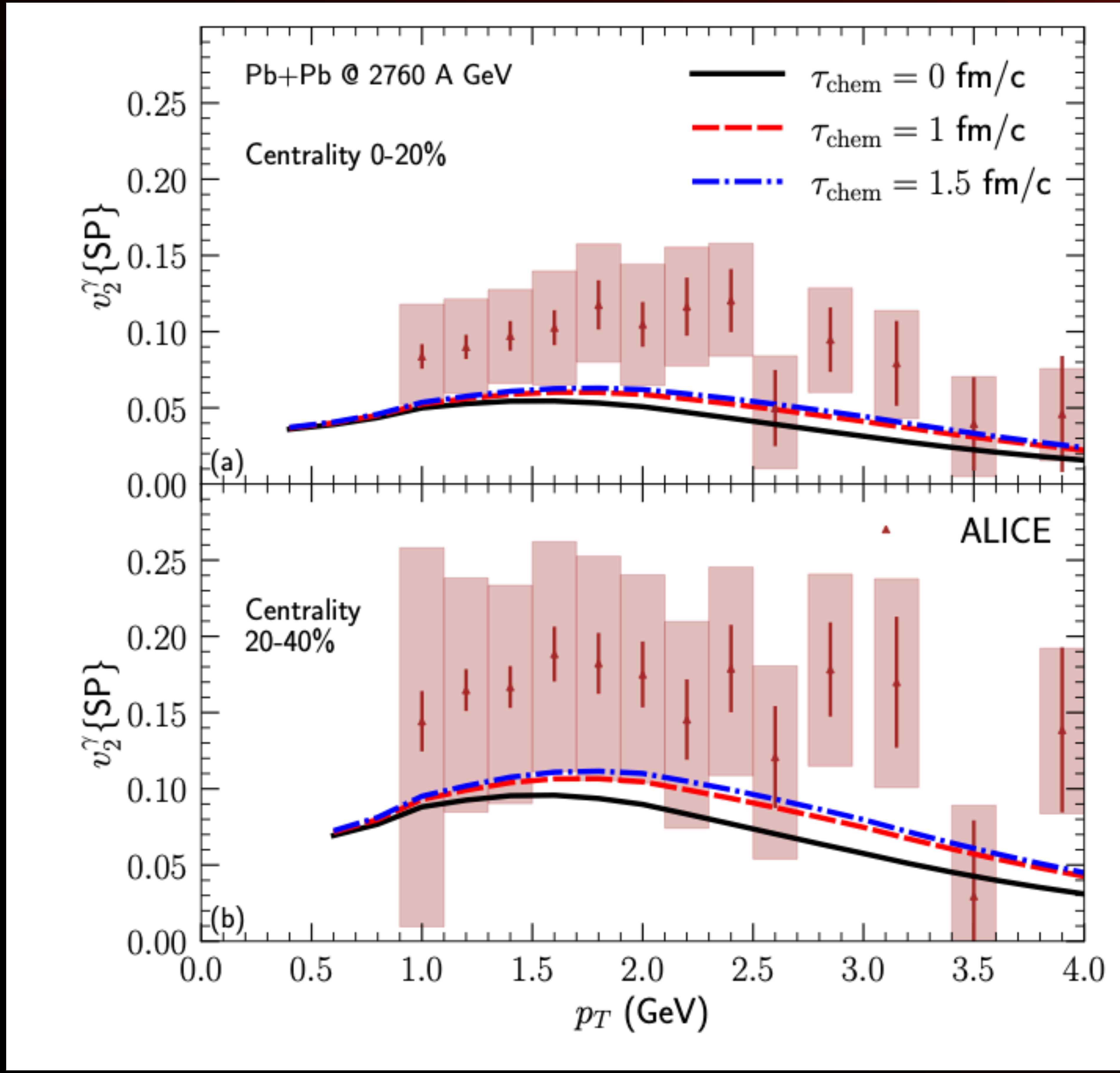


Photon v2 in ALICE

Subtitle



ALICE, *Phys.Lett.B* 789 (2019) 308-322



Acceptance Correction

Generate pairs with given mass and pT

(|y| < 0.8)

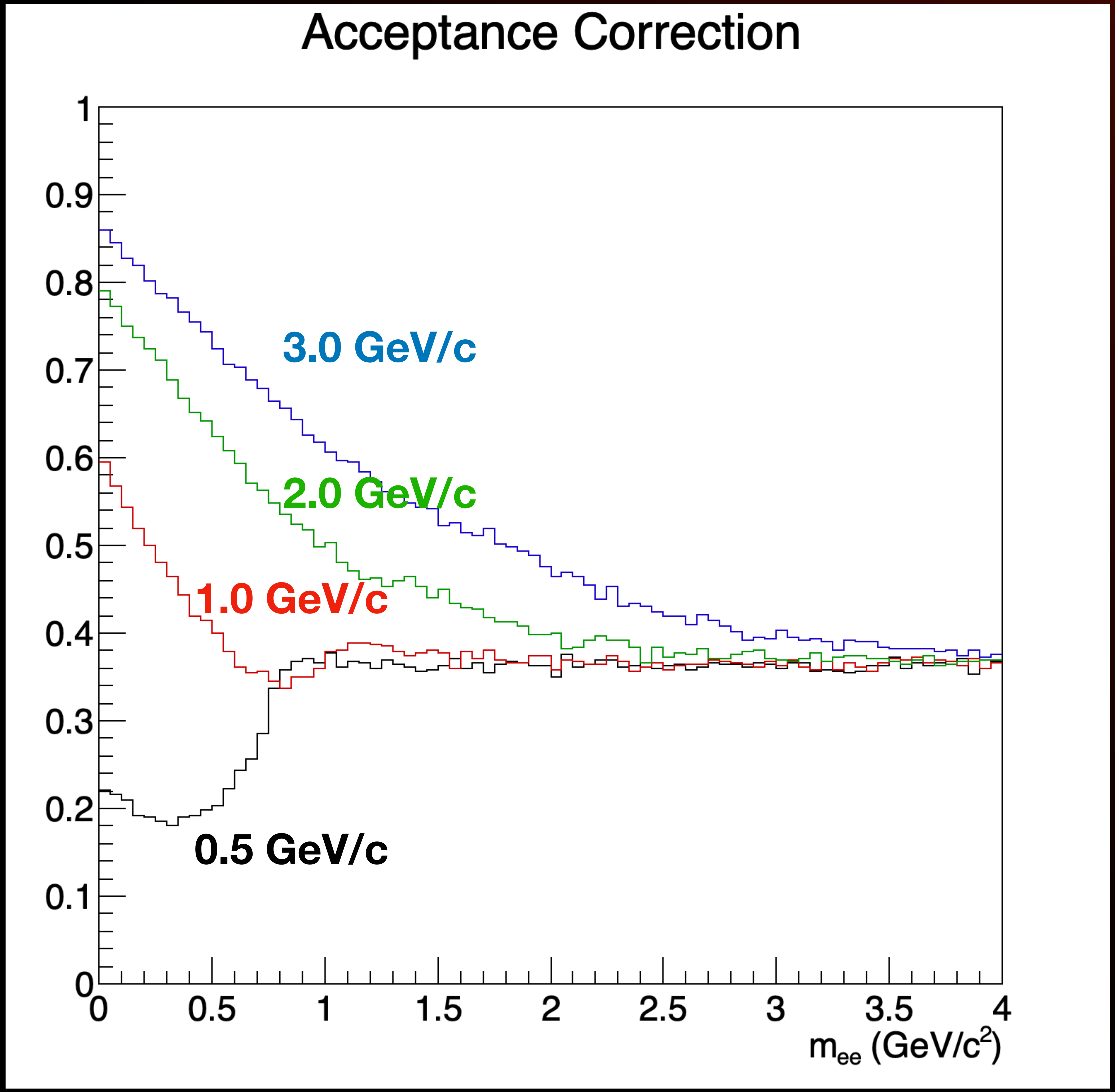
Let decay into dielectron

Reject based on kinematic cuts

(p_T > 0.2 GeV/c, |η| < 0.8)

This would be applied by dividing the spectrum by the given values.

So the correction would make the spectra harder at larger pT, thus resulting in higher Temperatures.



The SPS - CERES

Comparison of e+e− data with hadronic cocktail shows excess

Enhancement at low mass attributed to ππ annihilation?

Spectral shape dominated by ρ

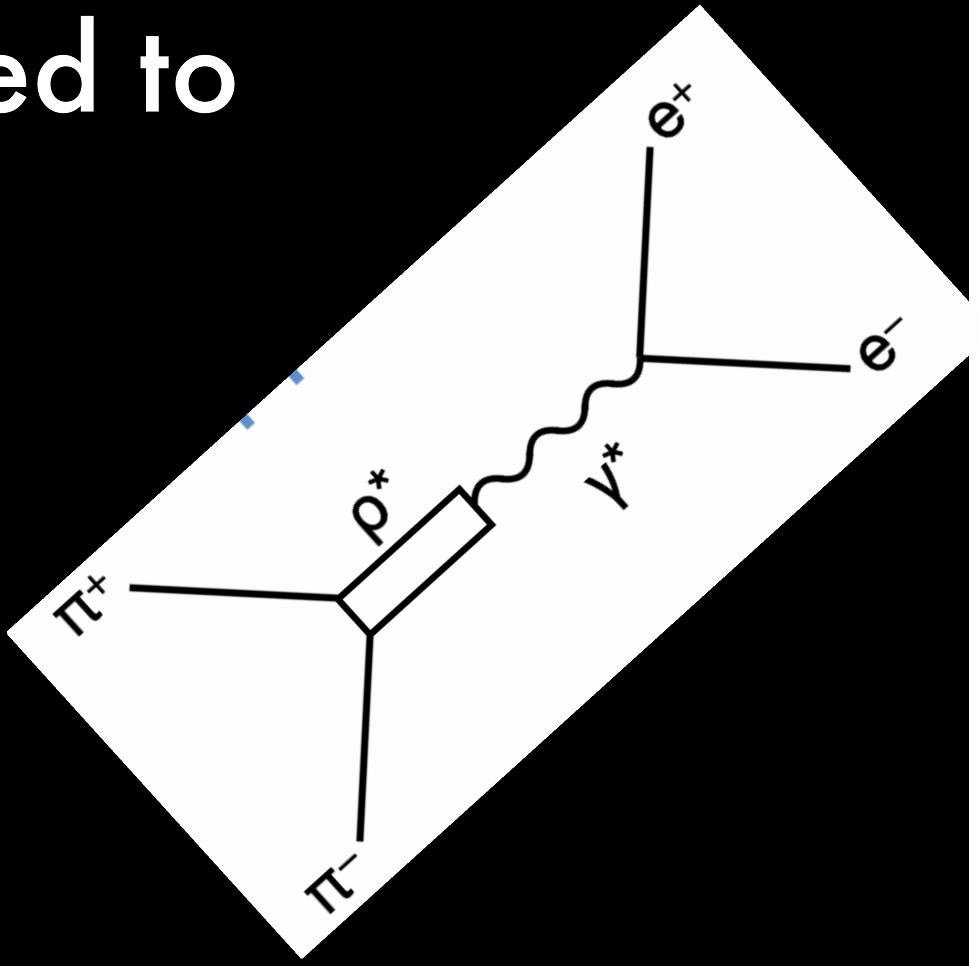
Possible contributions:

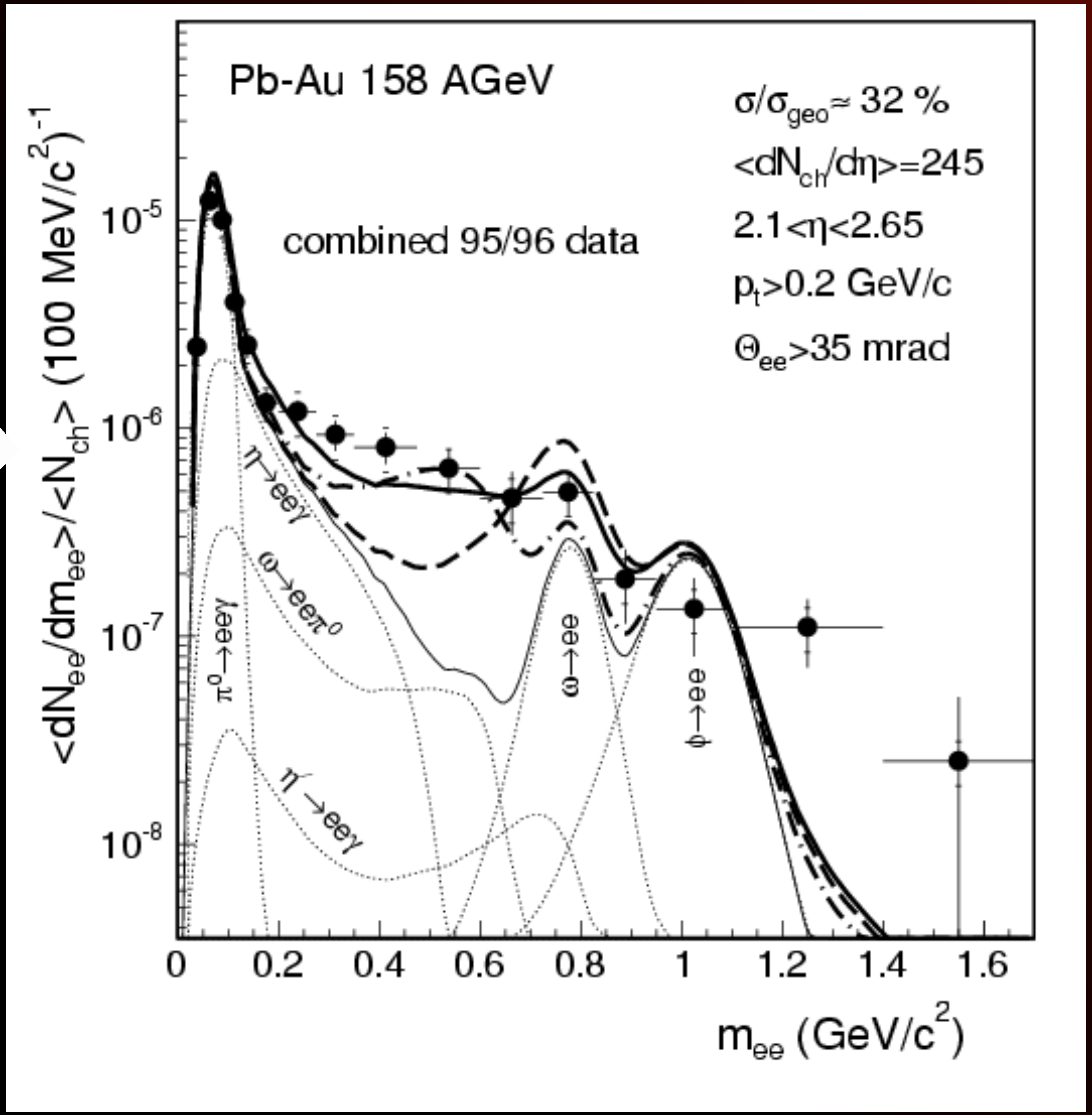
Vacuum ρ (just more than in pp, disfavoured)

Medium modified ρ

Dropping mass

Melting of the spectral function



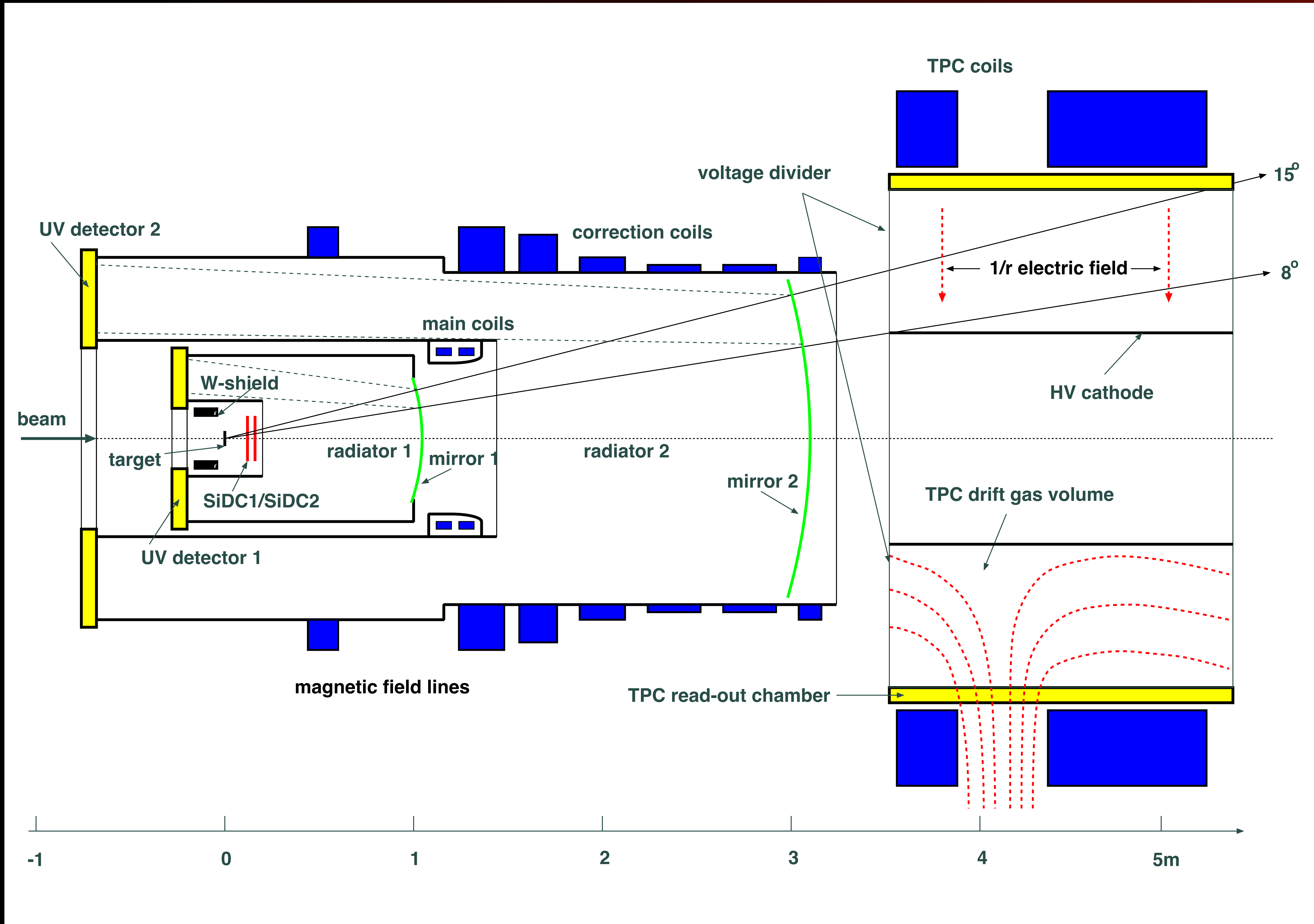


The SPS - CERES 2.0

Upgrade of the CERES experiment with a TPC

Better in momentum/mass resolution

dE/dx gives possibility for better electron identification



The SPS - CERES

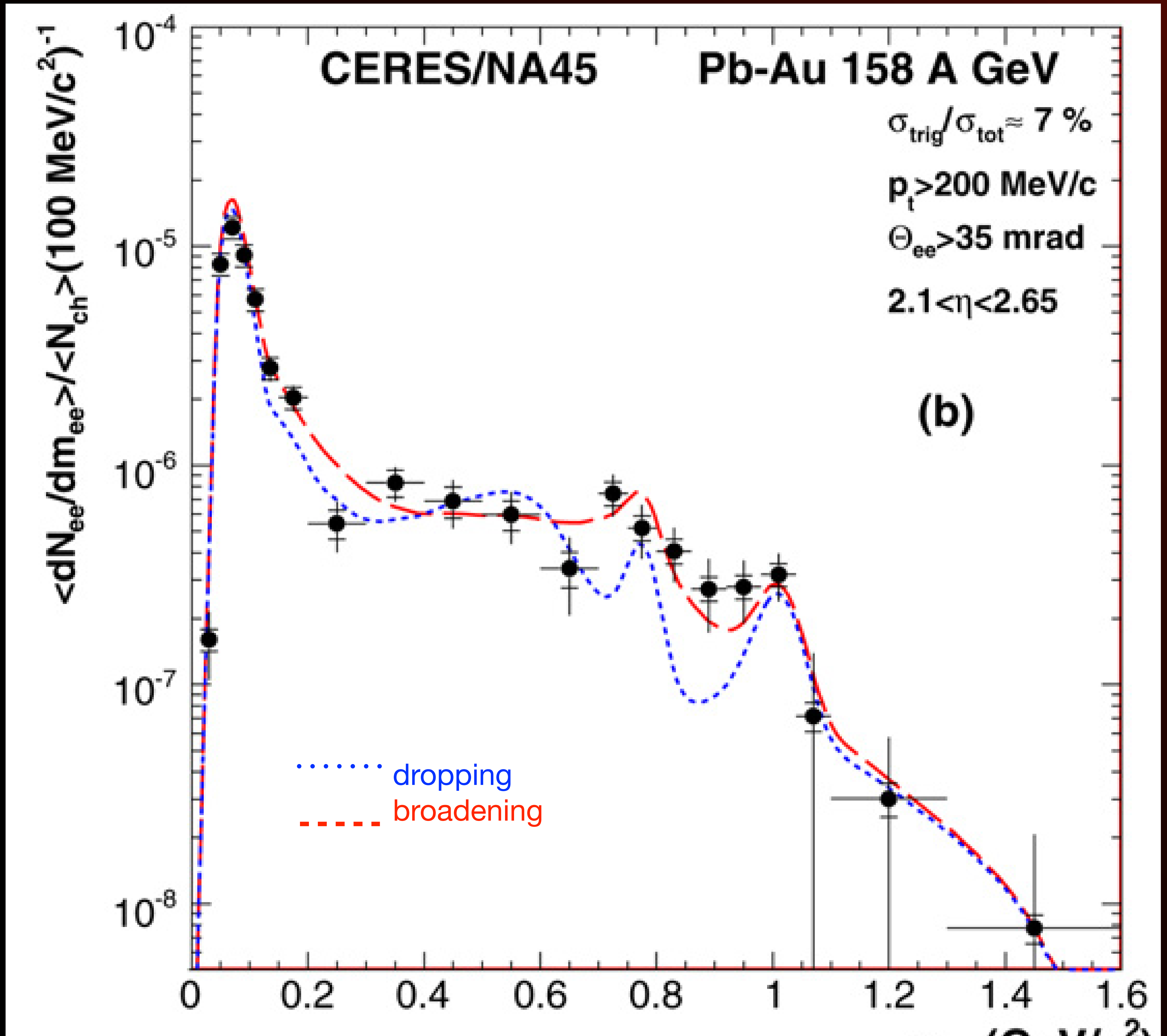
Persistance of previous results

Vacuum ρ not enough to reproduce data

In medium modification:

- Broadening ρ spectral function (Rapp and Wambach)
- Dropping ρ mass (Brown et al.)

Additional mass resolution and statistical precision needed to conclude on modification

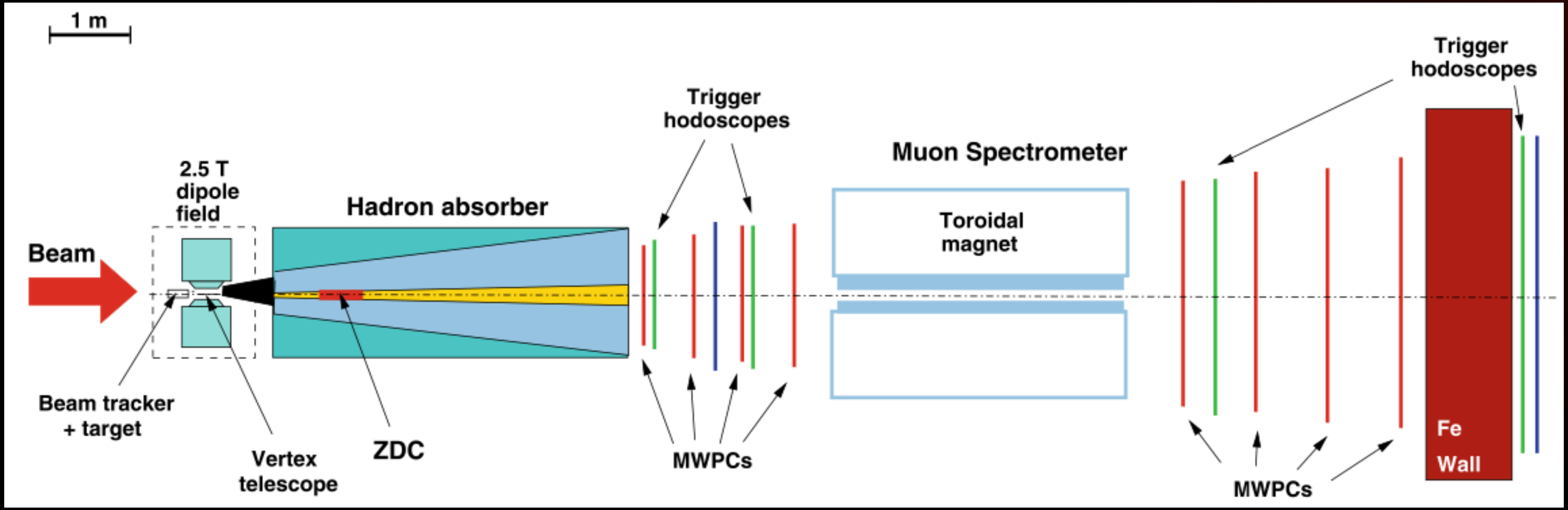


CERES, PLB 666 (2008) 425

The SPS - NA60

Muons instead of electrons → Trigger possible

Addition of vertex telescope to NA50 muon spectrometer gives possibility to match muons to tracks in the tracker → Higher mass resolution and information of muon origin



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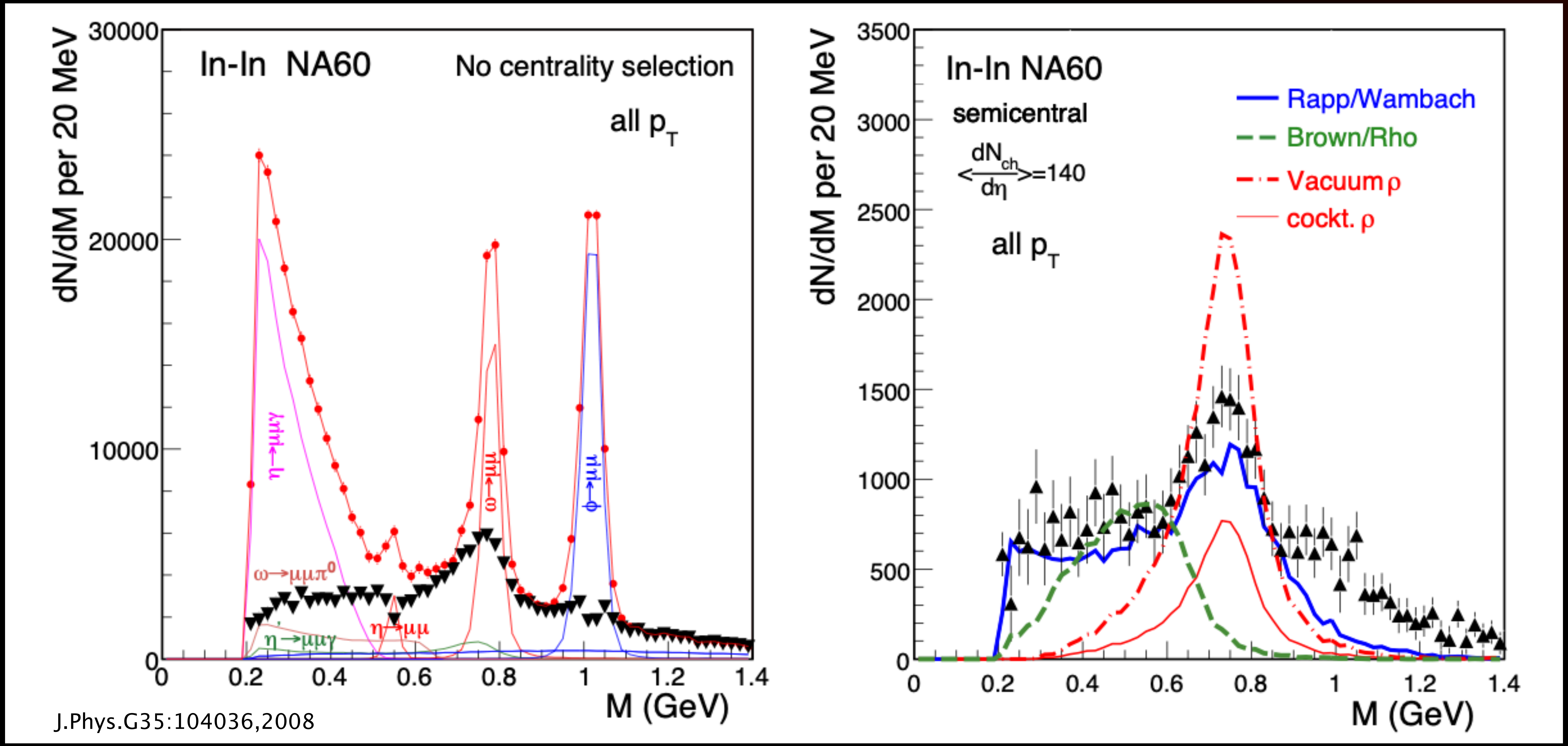


SPS - NA60

NA60 also measured the effective temprature as a function of mass

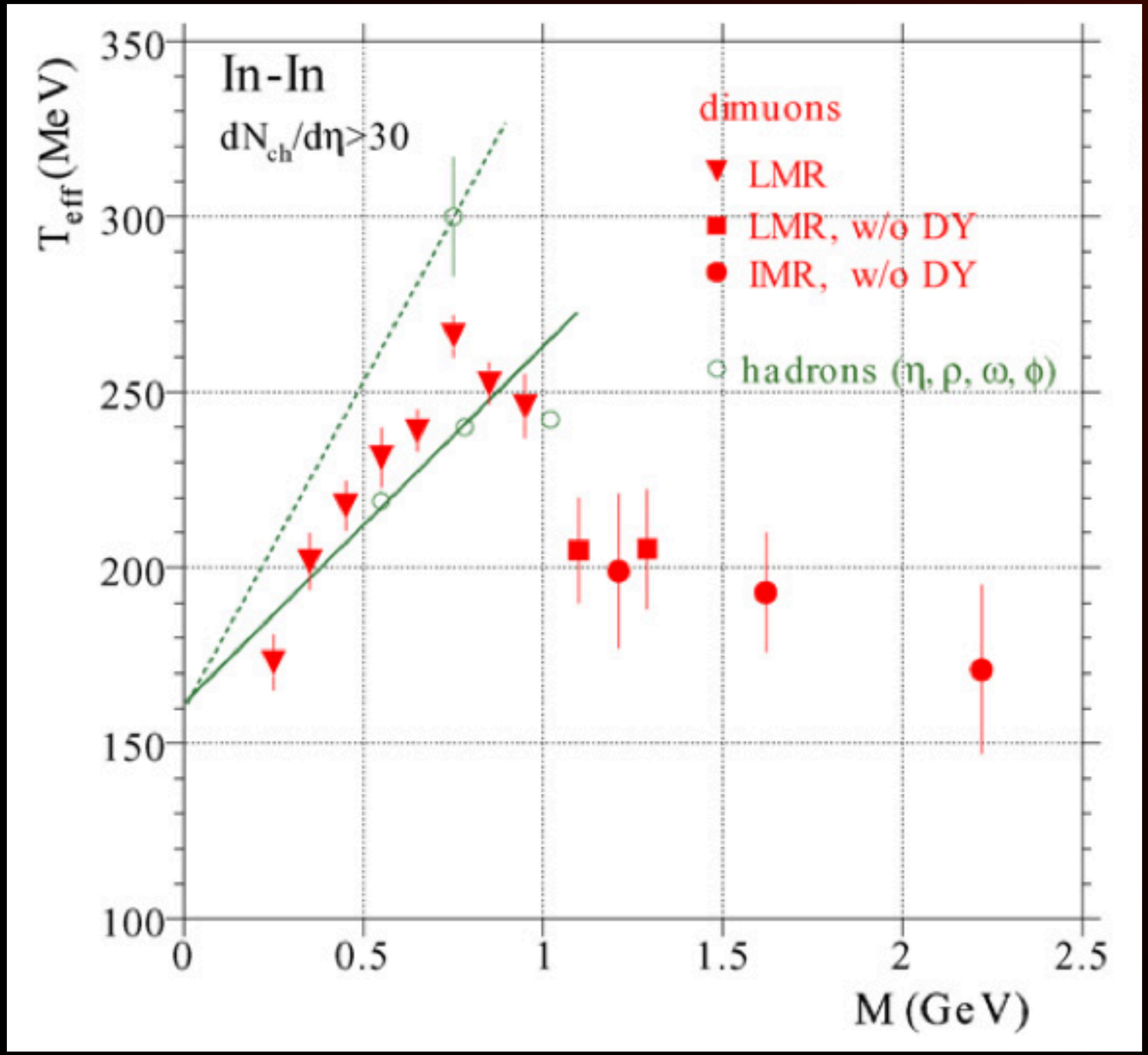
Fit of mT inverse slope in mass intervals

Low mass:

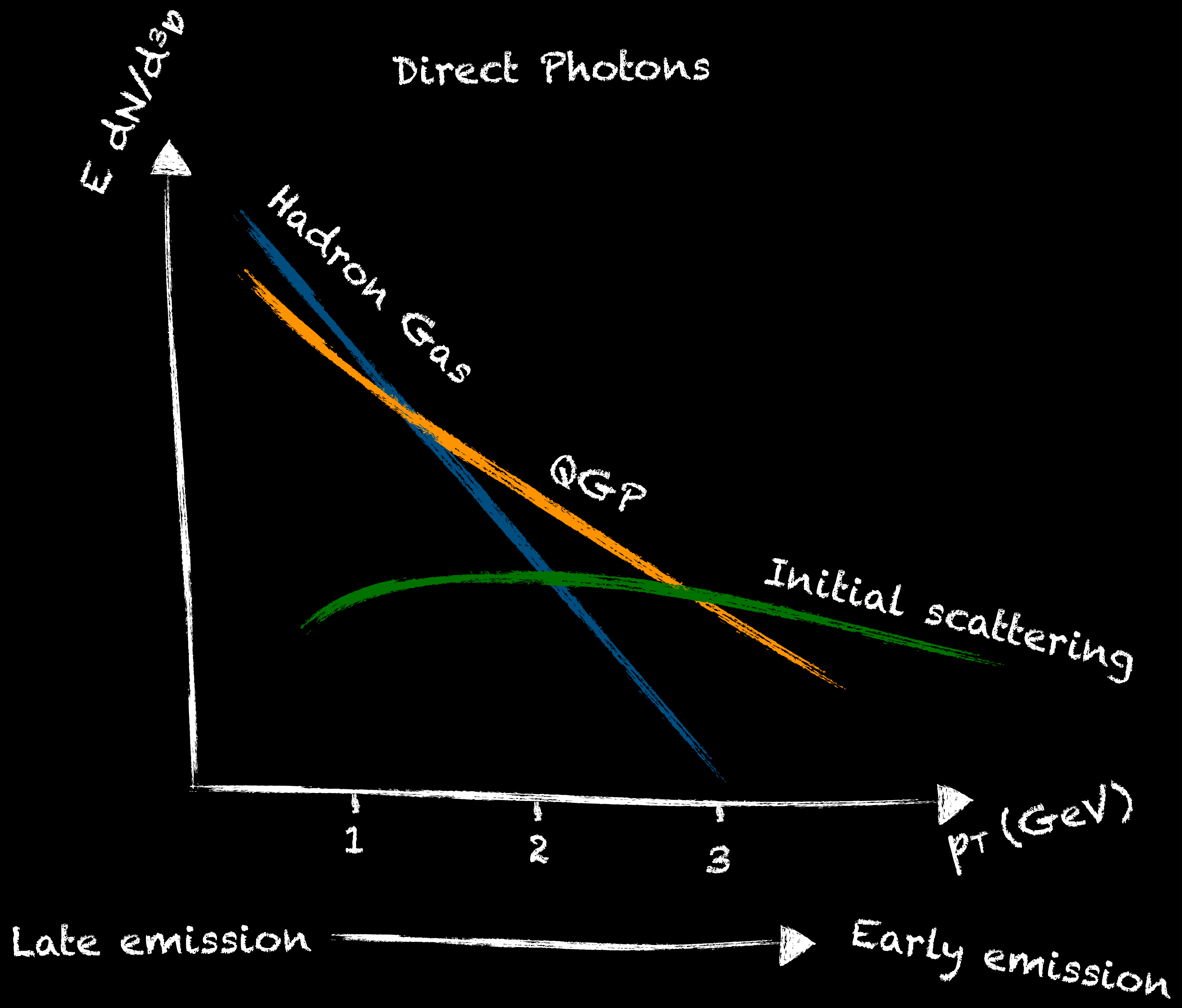
T_{eff} rises with mass, comparable with hadron → Hadronic Source

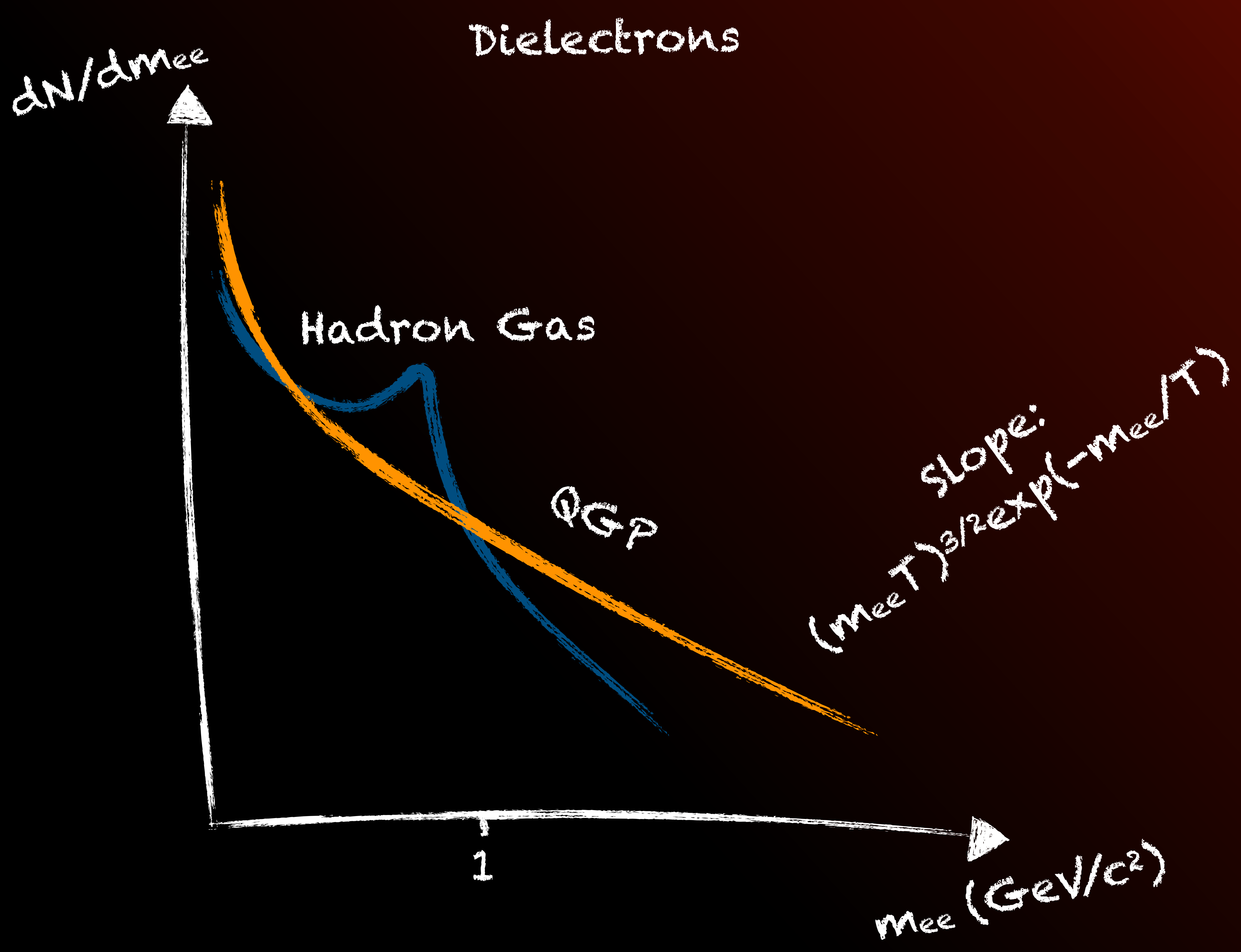
Intermediate mass:

Drop and almost constant value of ~200 MeV → Partonic source



The Sources


Direct Photons
E dN/d³p
Hadron Gas
QGP
Initial scattering
1
2
3
pT (GeV)
Late emission
Early emission


Dielectrons
dN/dmee
Hadron Gas
QGP
Slope:
(meeT)3/2exp(-mee/T)
1
mee (GeV/c²)