A Large Ion Collider Experiment

ALICE

DILEPTONS AND THERMAL RADIATION

Outline:

- Reminder: Electromagnetic probes of the QGP
- Status: Yellow report chapter
- Updates:
  - Theory (R. Rapp/pHSD)
  - Peripheral collisions (Spencer Klein, LBNL)

MICHAEL WEBER (SMI)
ON BEHALF OF THE «PHOTON AND DILEPTON» SUBGROUP
06.03.2018

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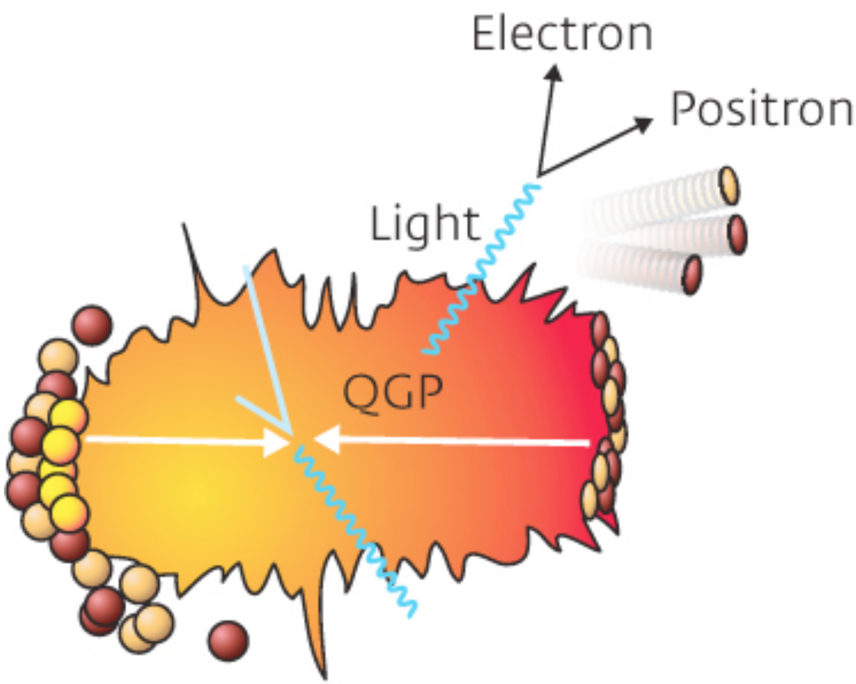
ELECTROMAGNETIC PROBES OF THE QGP



Dilepton emission rate in thermal equilibrium:

$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\,\mathrm{Im}\,\Pi^{\mu}_{\mathrm{em},\mu}(M,q;\mu_B,T) \times f^B(q_0;T)\ ,$$

Photons: measure γ (Calo, PCM)
Dileptons: measure e^+e^- or $\mu^+\mu^-$ pairs

- Couple to **EM current**
- **very low interaction** with QCD medium (no strong interaction)

- **Sensitive to**
  Photons:
  - Thermal radiation

  Dileptons:
  - Thermal radiation
  - Vector meson spectral shape
  - Beyond SM particles with $J^{PC}=1^{--}$ (e.g. dark photons)

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YELLOW REPORT PREPARATION

	Photons	Dielectrons	Dimuons
Spectra	No projections yet	ALICE LoI Fast simulation	ALICE LoI Improved heavy flavour systematics/ lower p_T threshold
Temperature	No projections yet	ALICE LoI Fast simulation	See above
Flow	No projections yet	ALICE LoI Fast simulation	?
Other	Comparison to virtual photon method	HF cross section/ DCA method?	

Other items (to be put to other chapter/WG?):

- Dark photons
- Peripheral collisions

Available
In preparation
Not for yellow report?

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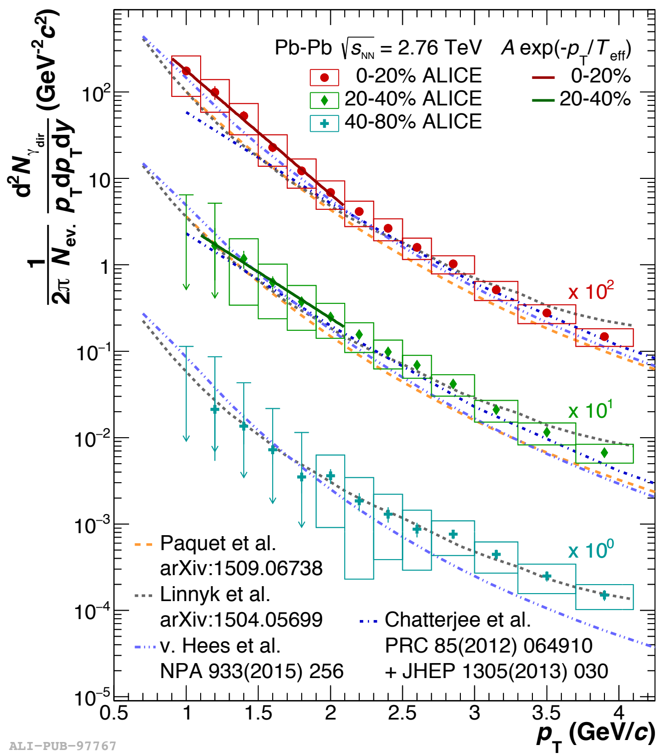
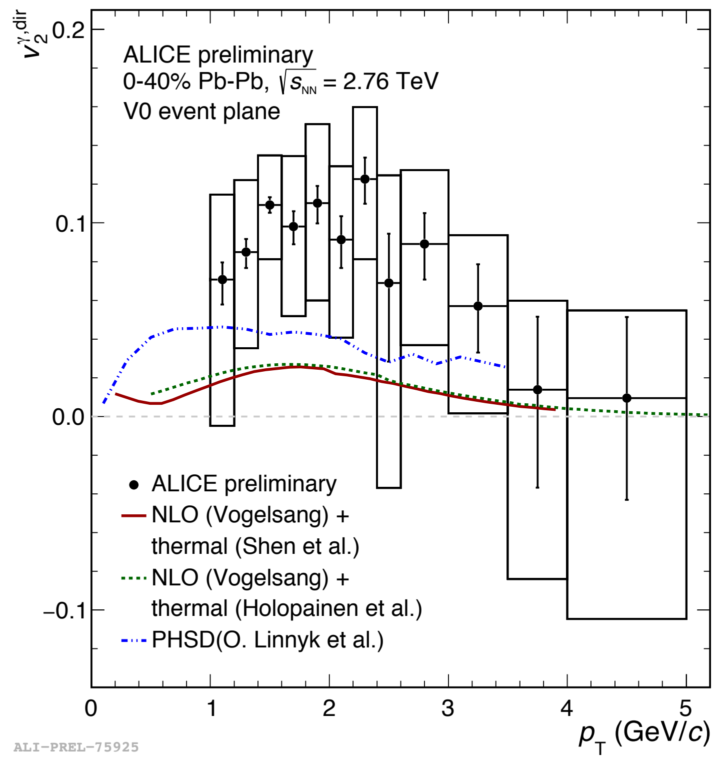
PHOTONS





- First measurement at LHC from soft exponential component of photon p_T spectrum (*ALICE, Phys.Lett. B754 (2016) 235*): ***T* ~ 300 MeV** (effective temperature averaged over system evolution)
- Projections for Run3/4 missing

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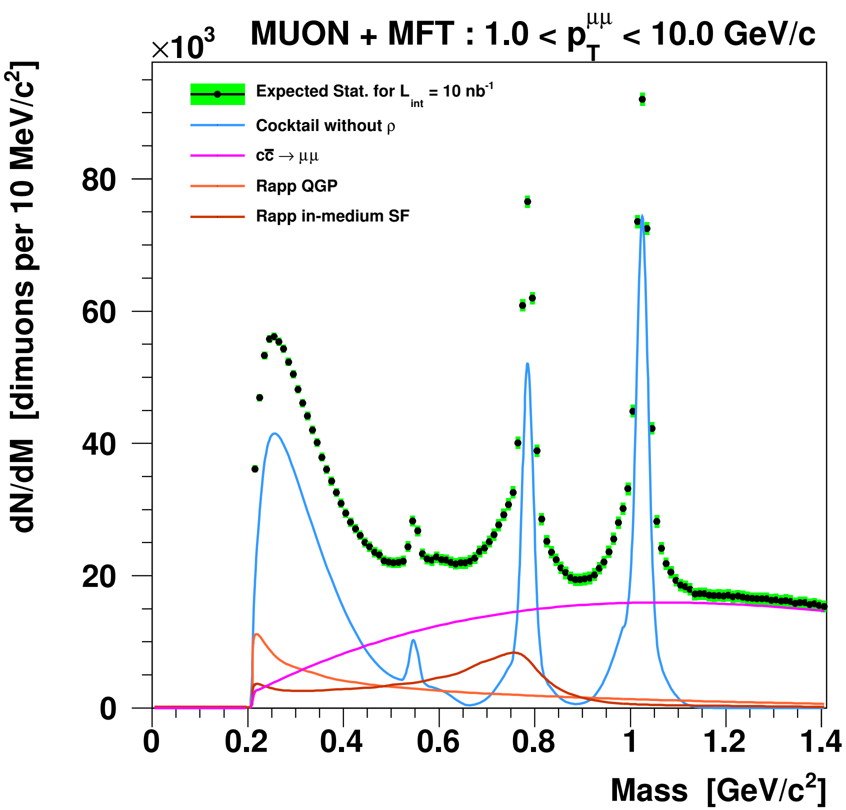
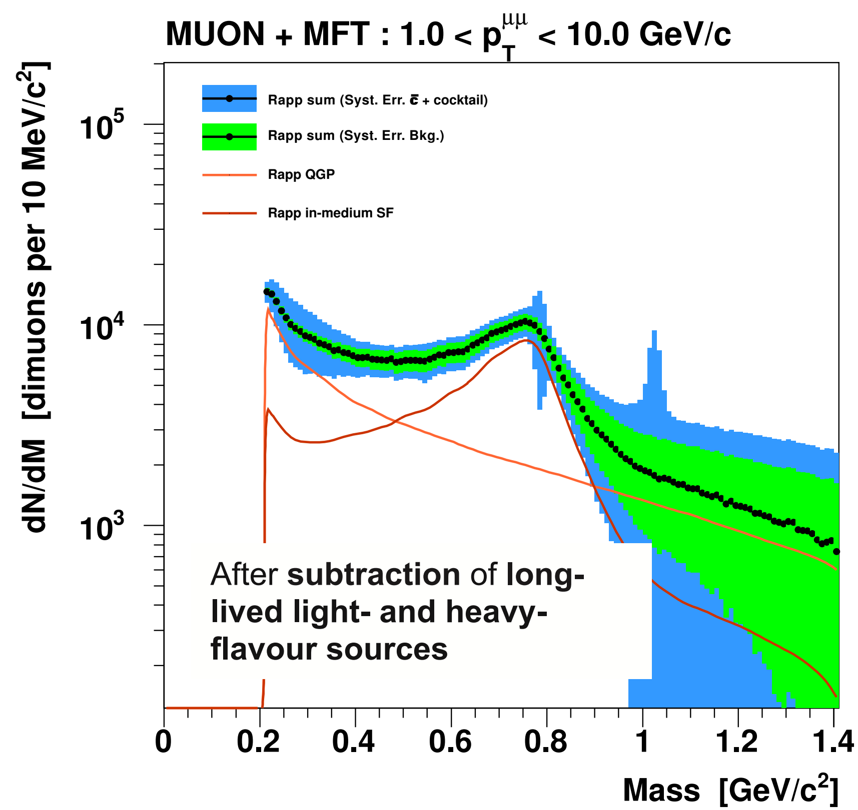
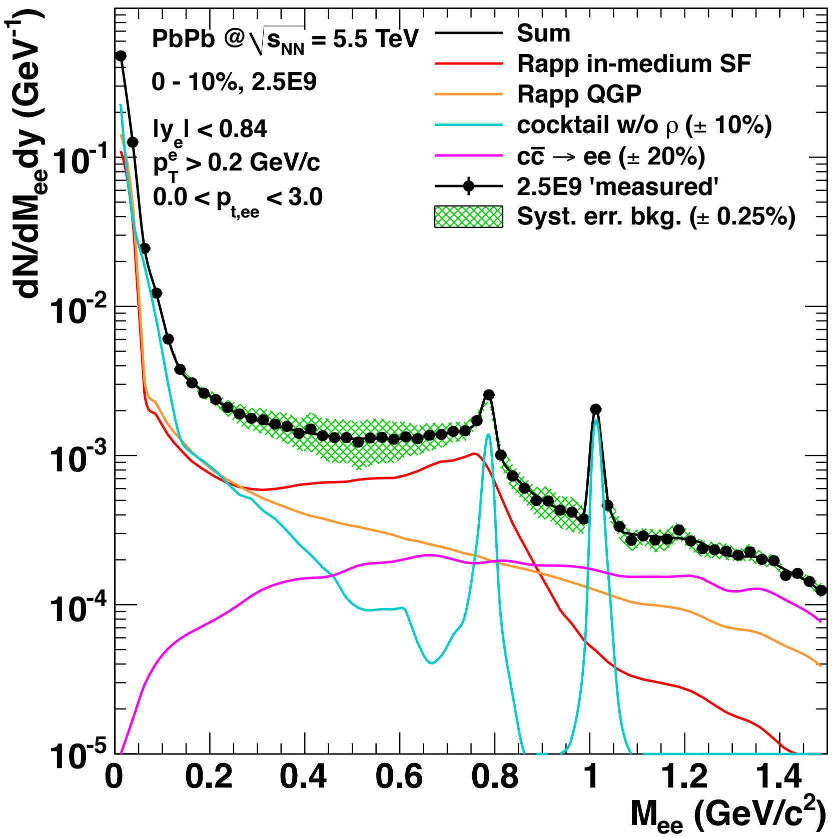
DIMUONS

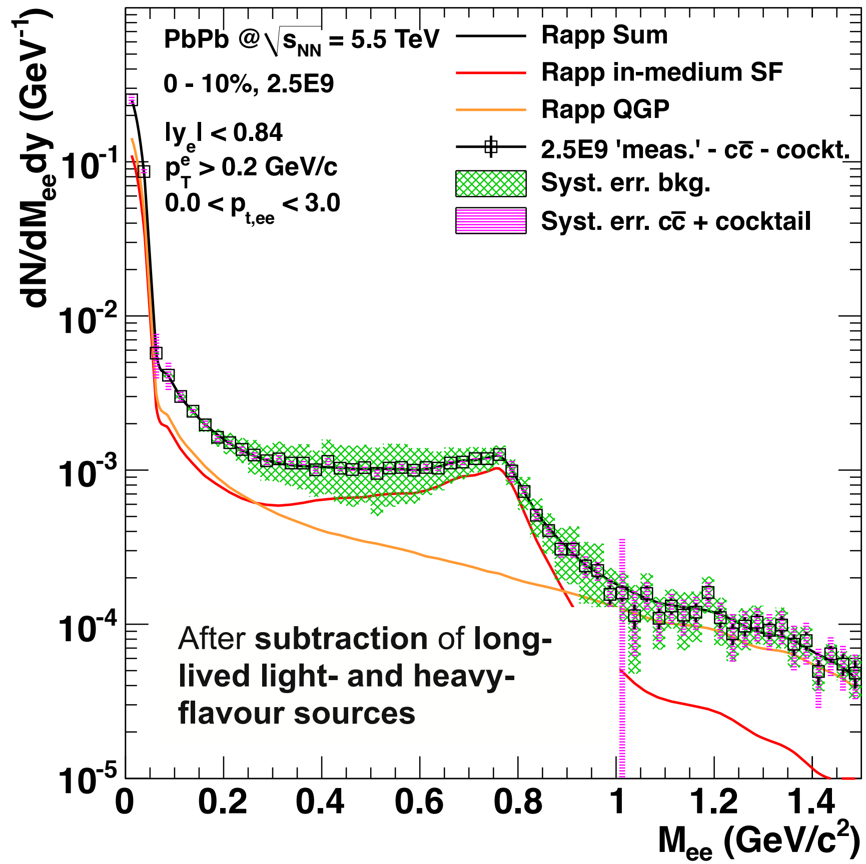




- Low mass spectral function with ~20% uncertainty
- Thermal radiation (M > 1GeV/c^2) difficult due to large HF systematic uncertainty

DIELECTRONS

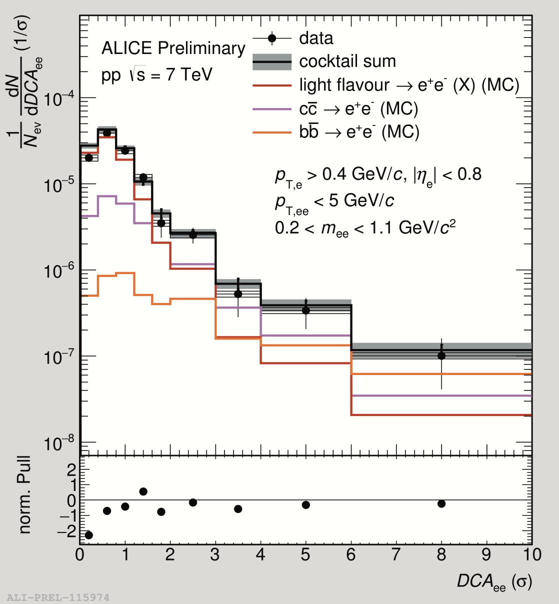




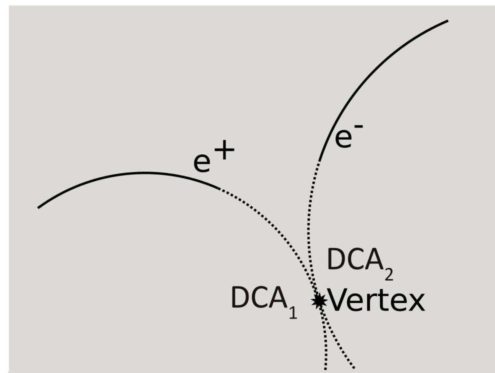
- Low mass spectral function with ~20% uncertainty
- Temperature and flow with ~10% uncertainty
- Results from fast simulation with more realistic geometry and photon conversion in preparation

DIELECTRONS – HF CROSS SECTION

Resonance Mass Region

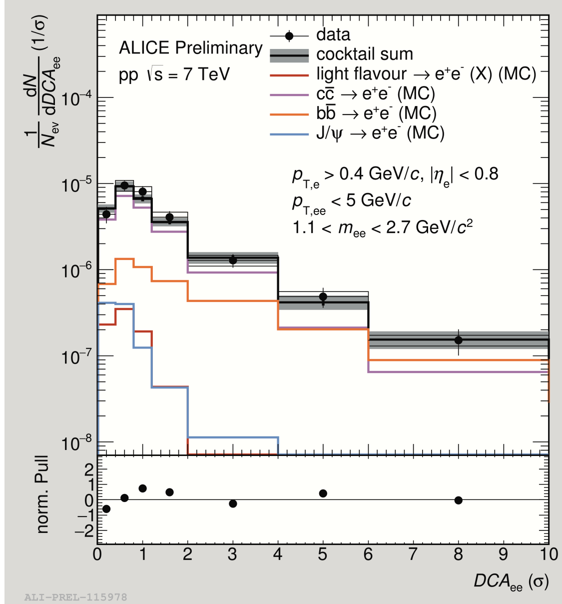


S. Scheid [ALICE], QM17



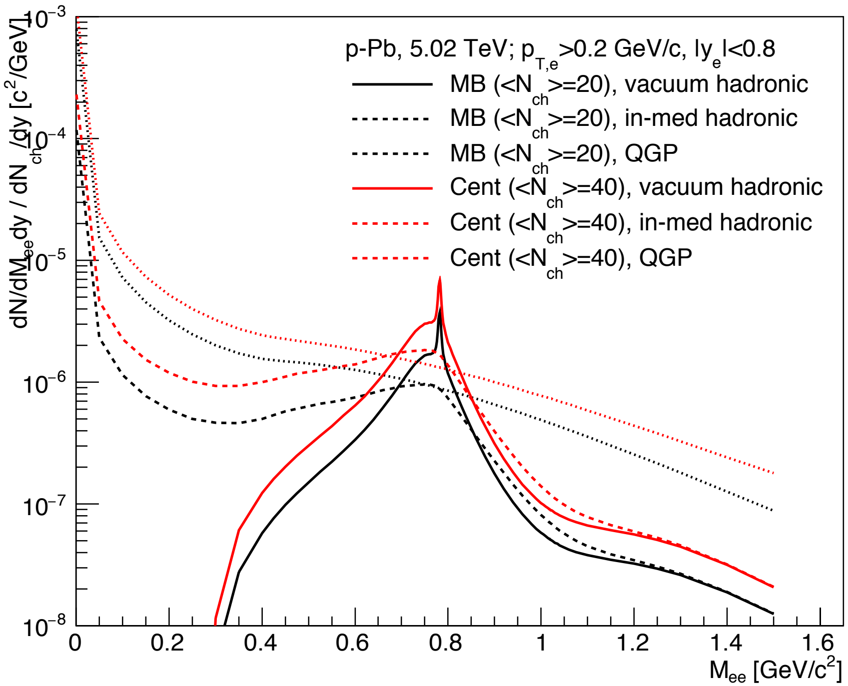
$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

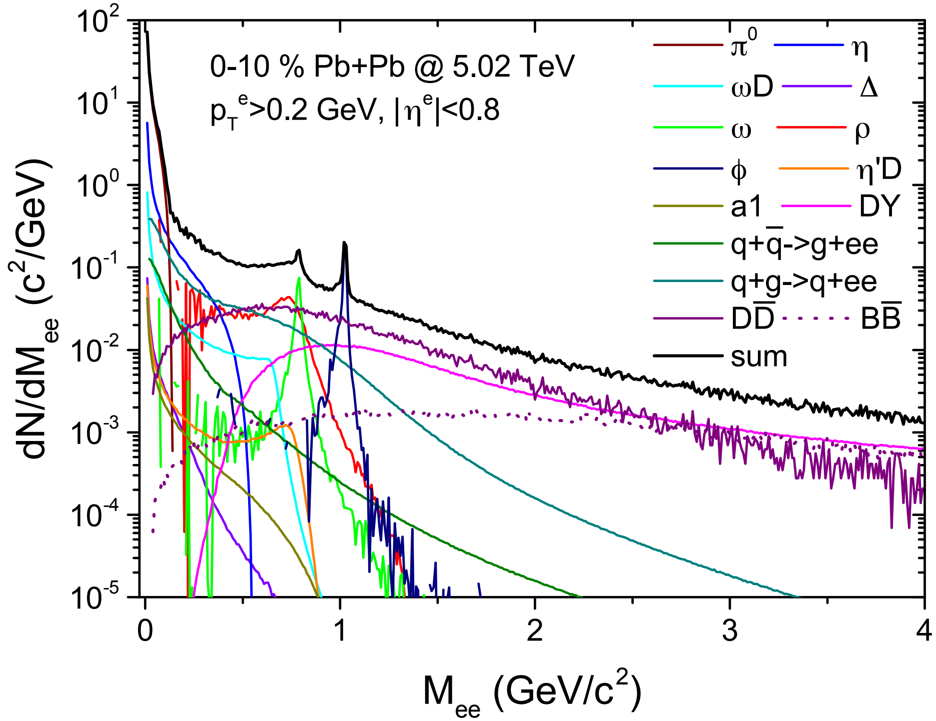
Intermediate Mass Region



- Run 1/2:
  - use combined m_{ee},$p_{T,ee}$ fit for heavy flavour cross section
  - Pair DCA as tool to distinguish between prompt and non-prompt sources
- Projections for Run3/4 missing:
  - better DCA_{ee} resolution
  - combined fit of m_{ee},$p_{T,ee}$,DCA_{ee}
  - $p_{T,ee}$ reach

NEW THEORY INPUT





Ralf Rapp (p-Pb)

pHSD model (Pb-Pb)

How to use? Other input needed?

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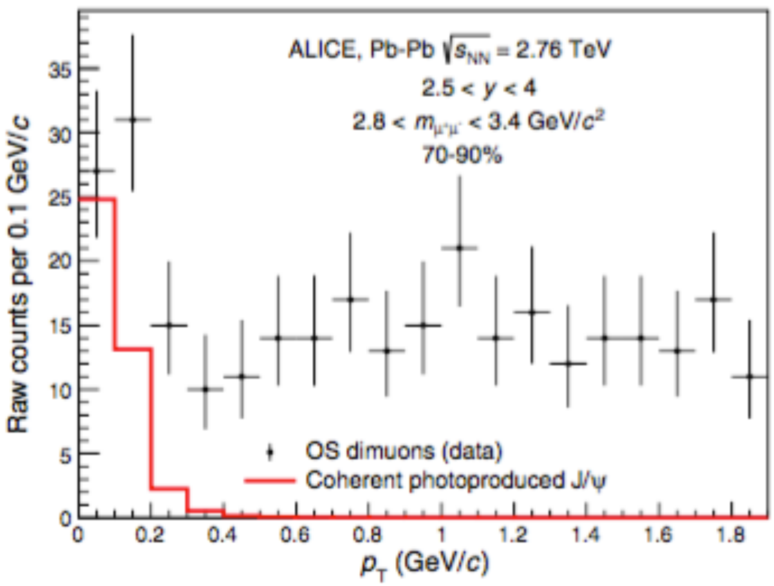
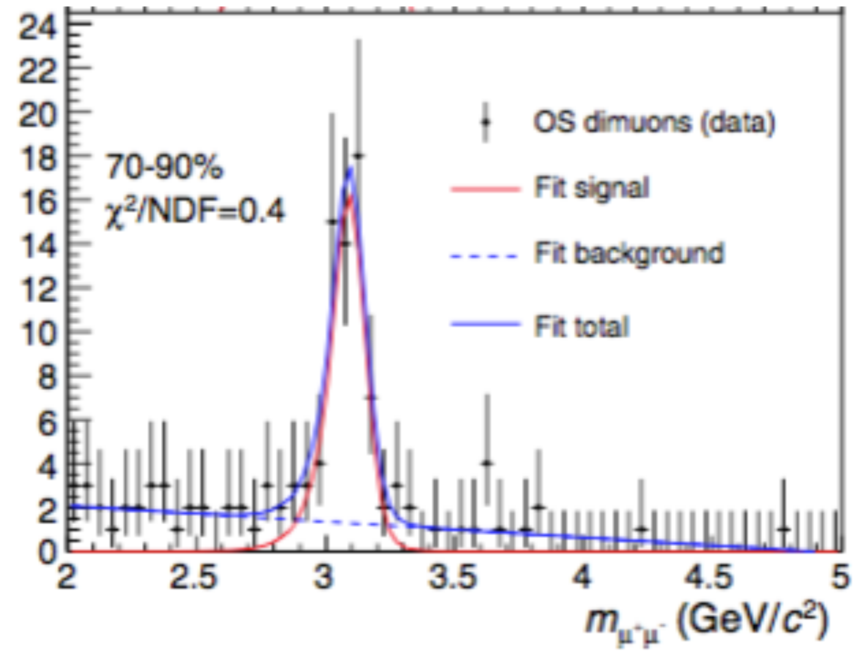
Production of low p_T e+e- pairs in peripheral collisions at HL-LHC

New input for discussion from Spencer Klein, LBNL
(full set of slides in the backup)

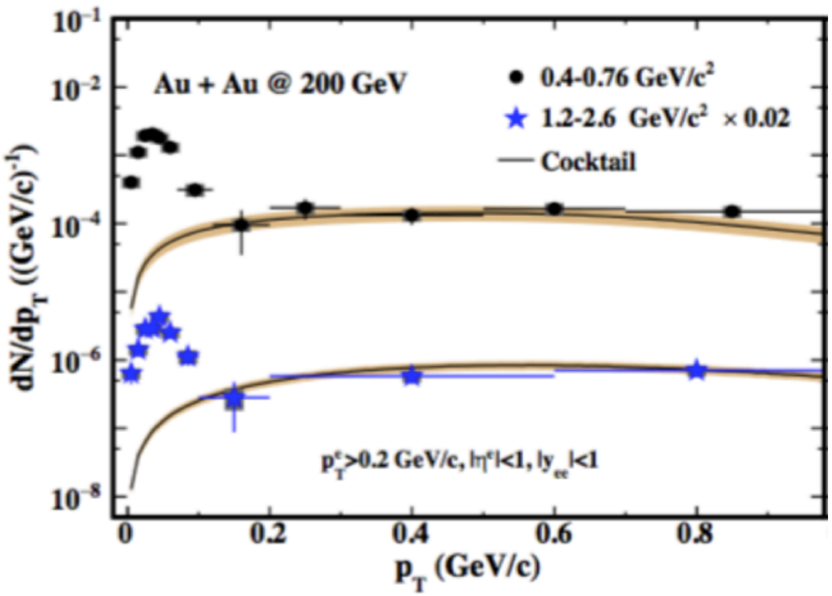
ALICE J/Ψ EXCESS

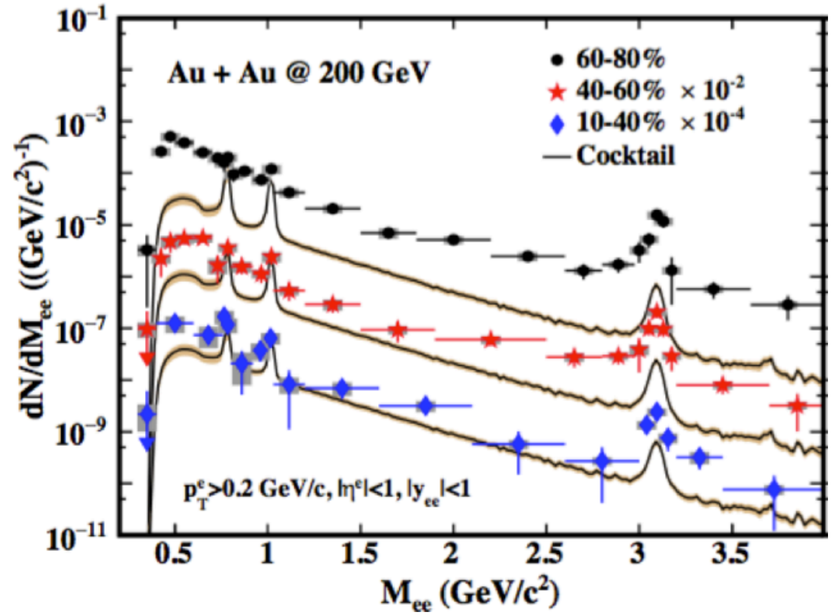




- J/ψ excess for p_T < 100 MeV/c in peripheral collisions
  - Magnitude is significant 70-90% centrality larger R_{AA}
- Low p_T peak not expected for any hadronic mechanism
  - Consistent with coherent photoproduction
- Seen at forward rapidity, 2.5 y < 4 (muon pairs)

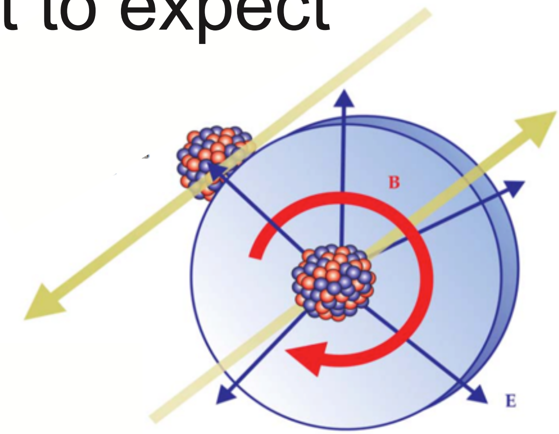
STAR LOW P_T E^+E^- EXCESS IN AU-AU & U-U





- Excess over hadronic cocktail for p_T < 150 MeV/c
- Continuum also at LHC?
  - No measurement yet

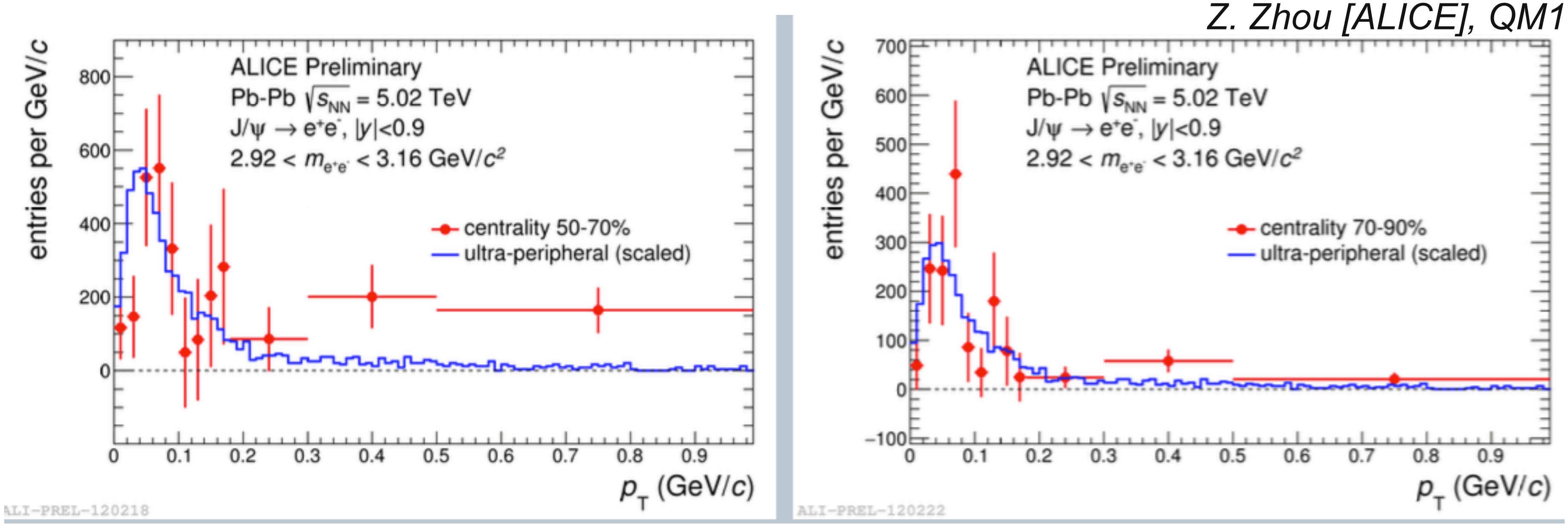
PRODUCTION OF LOW P_T E^+E^- PAIRS IN PERIPHERAL COLLISIONS AT HL-LHC



- Ultra-peripheral collisions tell us what to expect
  - Photons ala Weizsacker-Williams
    - Crossed E and B fields
  - Coherent $J/\psi \rightarrow$ ee photoproduction
    - Peaked at M_{ee}= J/ψ mass
  - $\gamma\gamma$ -> ee
    - Broadband emission, peaked at low M_{ee}
    - Individual lepton rapidity distribution is very very broad
      - Cross-section is very large, but mostly invisible in central detectors
      - Individual lepton p_T spectrum much softer than from J/ψ
  - Both have emission peaked with pair p_T < 100 MeV/c
    - Two mechanisms, but surprisingly similar pair p_T spectra
- What can we learn from these reactions?

p_T SPECTRUM OF J/Ψ IN PERIPHERAL COLLISIONS

Z. Zhou [ALICE], QM17



- Spectrum is consistent with UPC J/ψ photoproduction data
  - Drop at low p_T due to interference between two directions
    - Smaller |b|, so interference extends to higher p_T than for UPCs
    - Could reduce total cross-section
- Spectator-only target has a different matter distribution than full nucleus target.
  - Different p_T spectrum + some azimuthal anisotropy
- p_T spectrum depends on size of the coherence region

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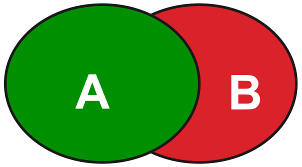
WHAT CAN WE LEARN?

- Most of J/ψ photoproduction amplitude is from spectator region
  - Expanding plasma might destroy long-lived (10^{-20} s) J/ψ
    - Rate measurement is interesting, but more precise measurements, theory needed!
- J/ψ p_T angular distribution is Fourier transform of coherent production region
  - I. e. region A minus region B



- The azimuthal distribution is sensitive to the event plane
- Other items connected to **low mass** dilepton physics (short lived ρ meson)?
- Continuum?

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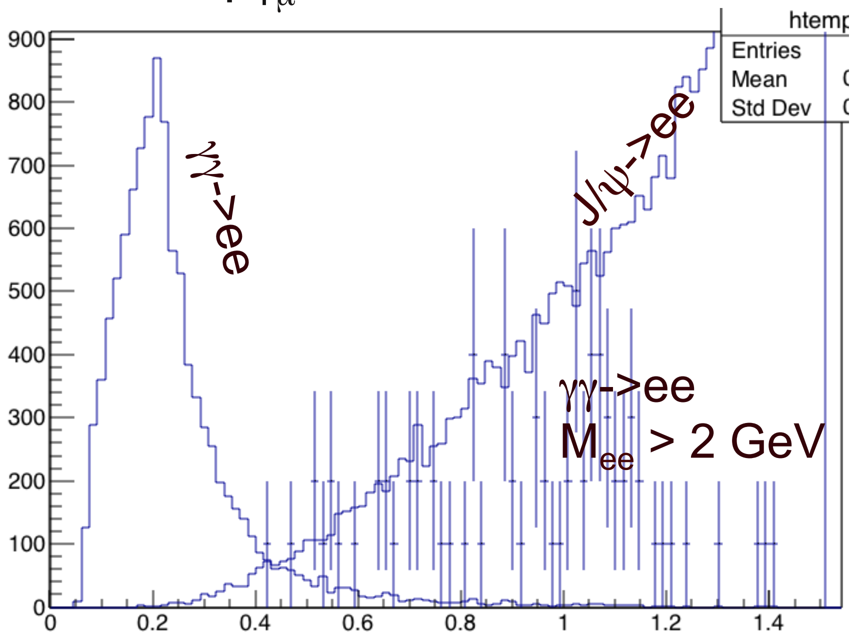
SINGLE LEPTON PT DISTRIBUTIONS

- J/ψ (or ρ/ω/ϕ) -> ee and γγ-> ee share many characteristics
  - Similar pair p_T spectra
  - Hard to distinguish rapidity distributions in central detectors
- The angular distribution of the final state l^+l^- is very different
  - -> Very different lepton rapidity and p_T distributions
  - With $p_{T\mu}$ > 1 GeV/c cut, ALICE sees J/ψ -> μμ only



Lepton p_T w/ STAR cuts
STAR γγ-> ee
STAR J/ψ -> ee
STAR γγ->ee w/ M_{ee} > 2 GeV/c
J/ψ are in UPC, but this doesn't affect lepton spectra much

Arbitrary normalization

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CONCLUSIONS (PERIPHERAL COLLISIONS)

- STAR and ALICE have observed an excess of dilepton pairs with $p_T < \sim 100$ MeV/c in peripheral heavy ion collisions
  - STAR sees J/ψ + a mass continuum
  - ALICE sees only J/ψ
- The rate and kinematics are consistent with expectations from coherent photoproduction and $\gamma\gamma \to l^+l^-$

- HL-LHC will collect samples 140 times larger than the current ALICE measurement.
  - The J/ψ rate and cross-section are sensitive to the size of the production region, and the possible destruction of spectator-region J/ψ by the expanding fireball.
  - The J/ψ p_T distribution might be used to provide an independent determination of the reaction plane, allowing for cross-checks with other methods.
  - More theoretical work is needed to fully benefit from this data.

  - Technical: should go to this subchapter or somewhere else?

CONCLUSIONS

	Photons	Dielectrons	Dimuons
Spectra	No projections yet	ALICE LoI Fast simulation	ALICE LoI Improved heavy flavour systematics/ lower p_T threshold
Temperature	No projections yet	ALICE LoI Fast simulation	See above
Flow	No projections yet	ALICE LoI Fast simulation	?
Other	Comparison to virtual photon method	HF cross section/ DCA method?	

Other items (to be put to other chapter/WG?):

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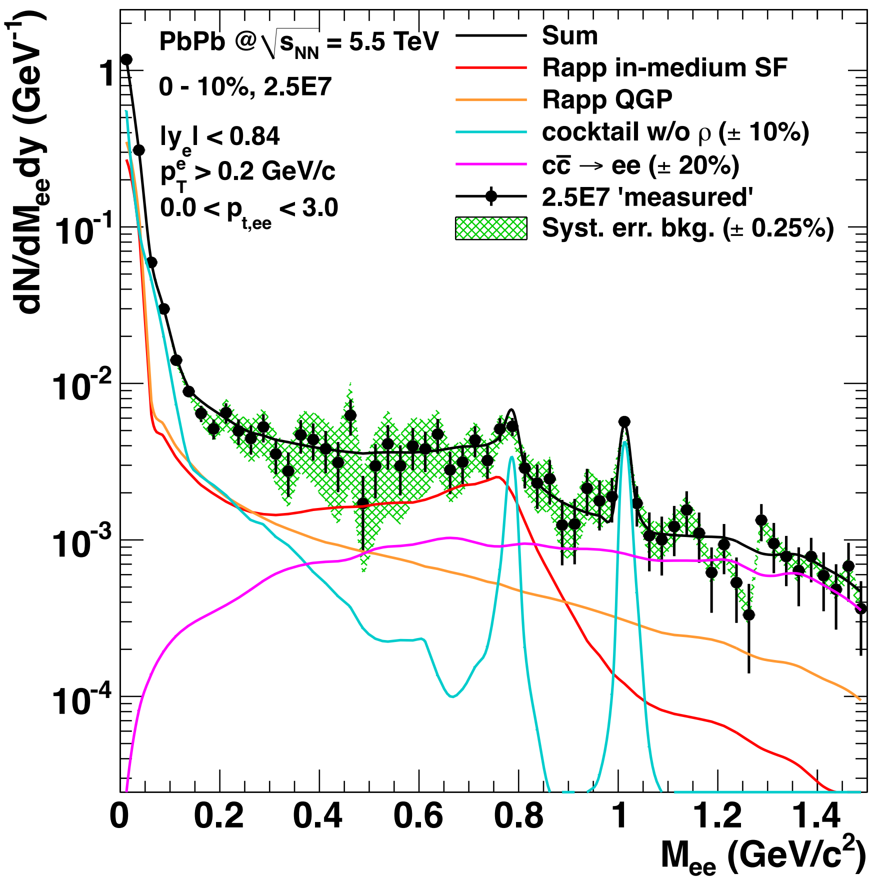
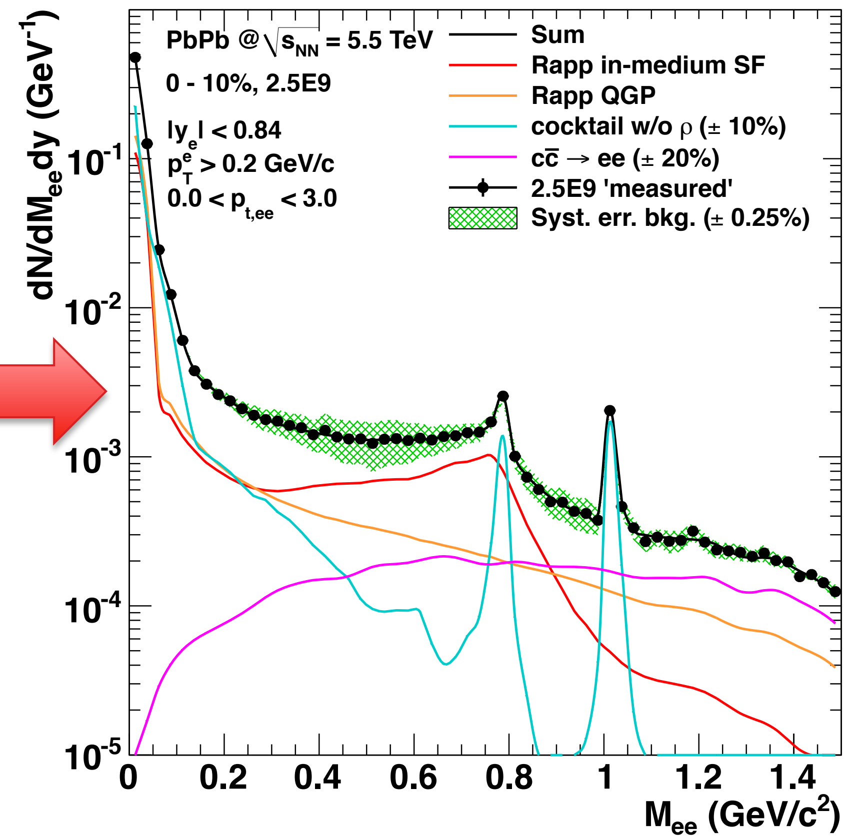
BACKUP

UPGRADE IMPROVEMENT





- Current ITS
- Current readout

- New ITS: less conversion, better DCA resolution
- New readout: x100 statistics

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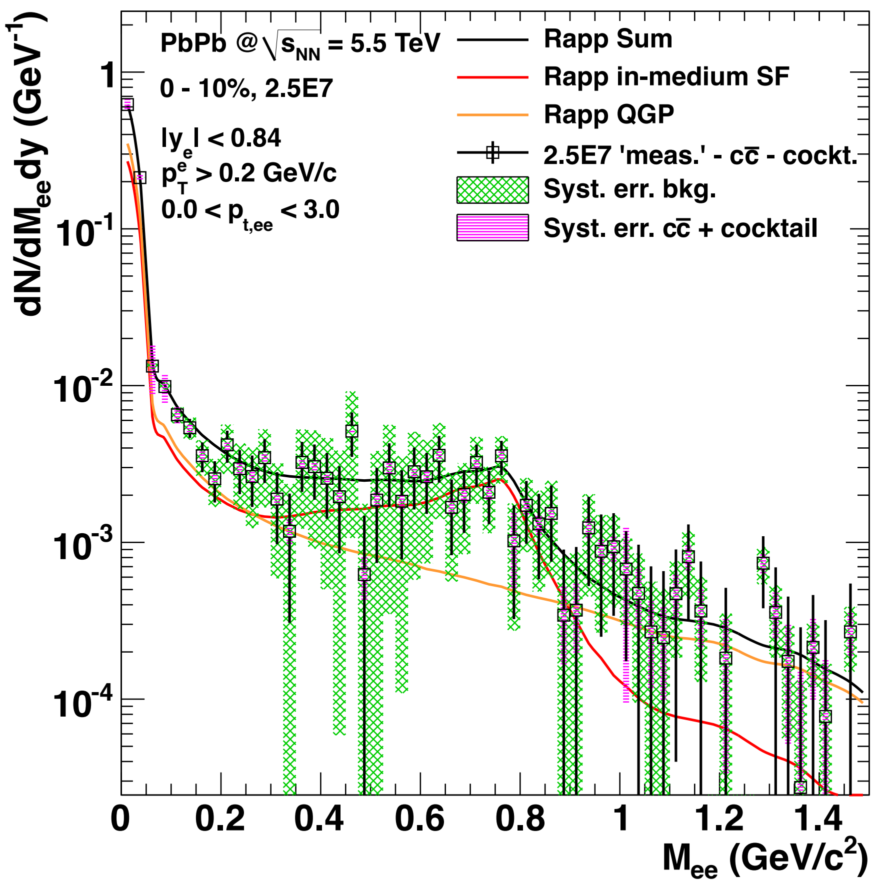
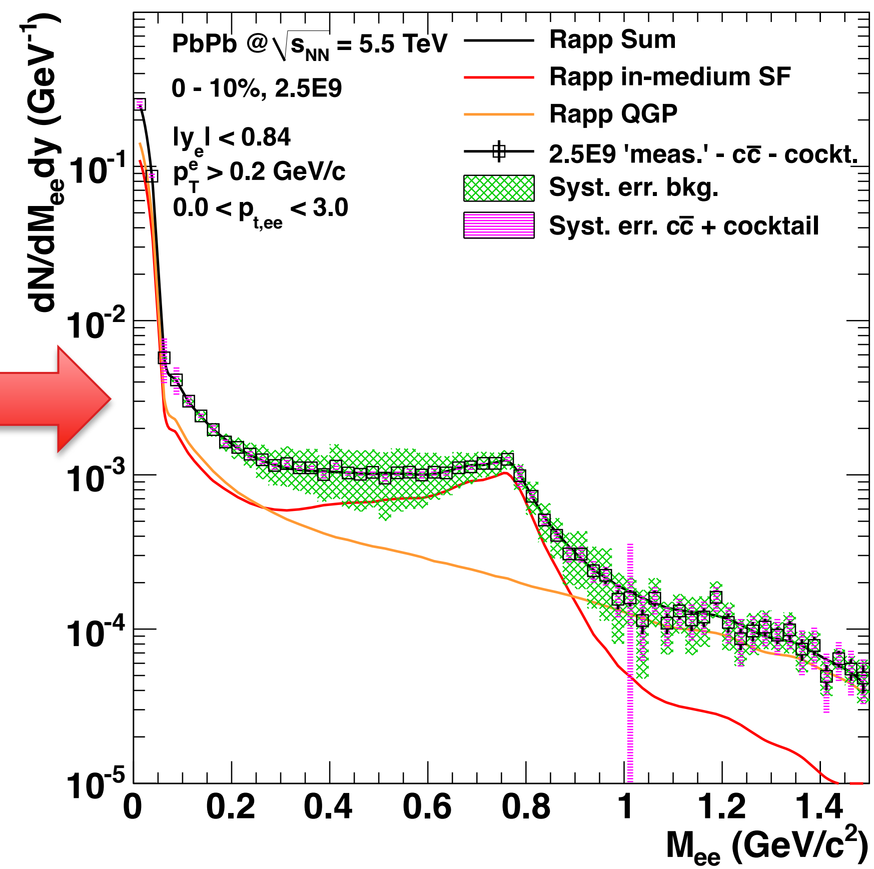
SPECTRAL FUNCTION

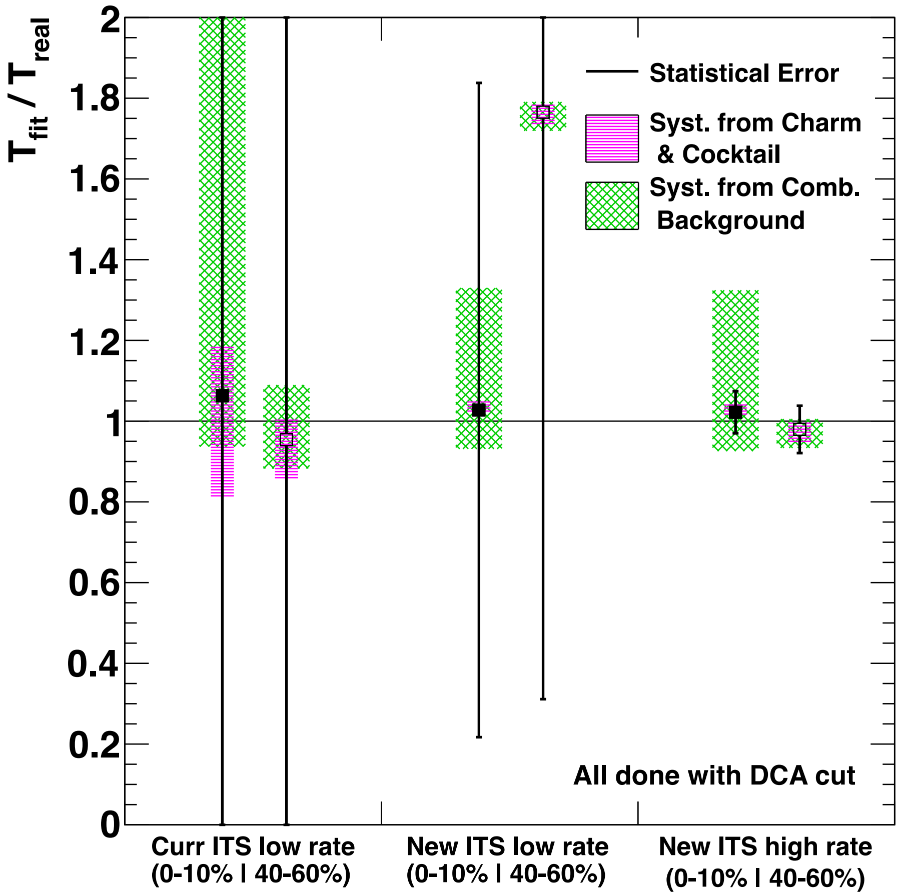




Low mass spectral function with ~20% uncertainty

After **subtraction** of **long-lived light- and heavy-flavour sources**

TEMPERATURE EXTRACTION



From a fit to the invariant mass spectrum from 1.1 to 1.5 GeV/c^2

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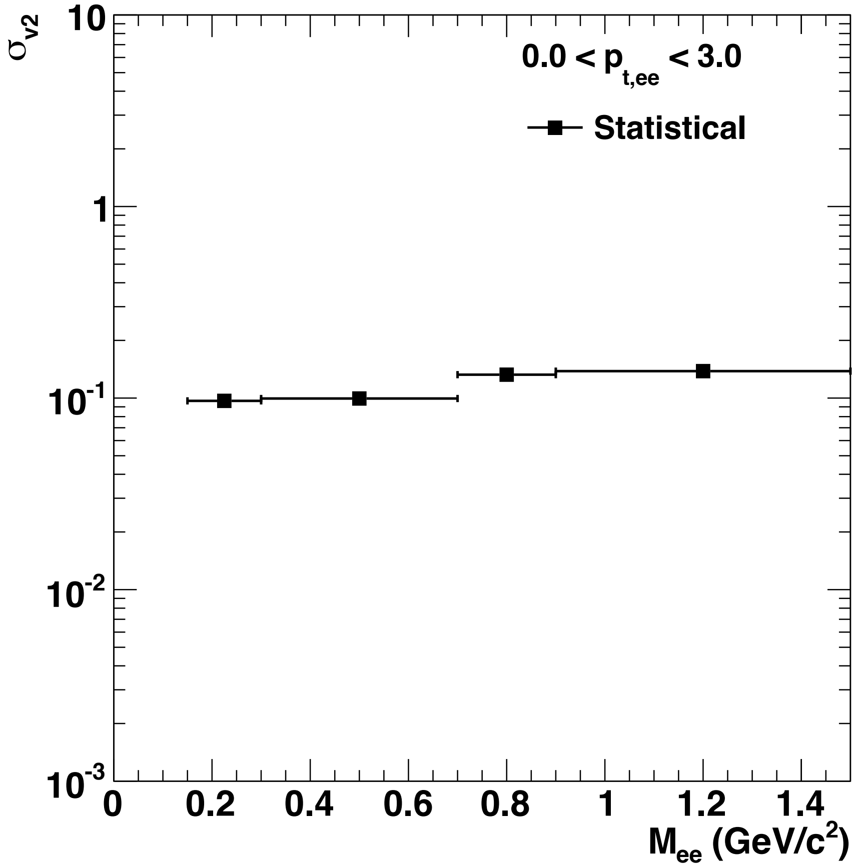
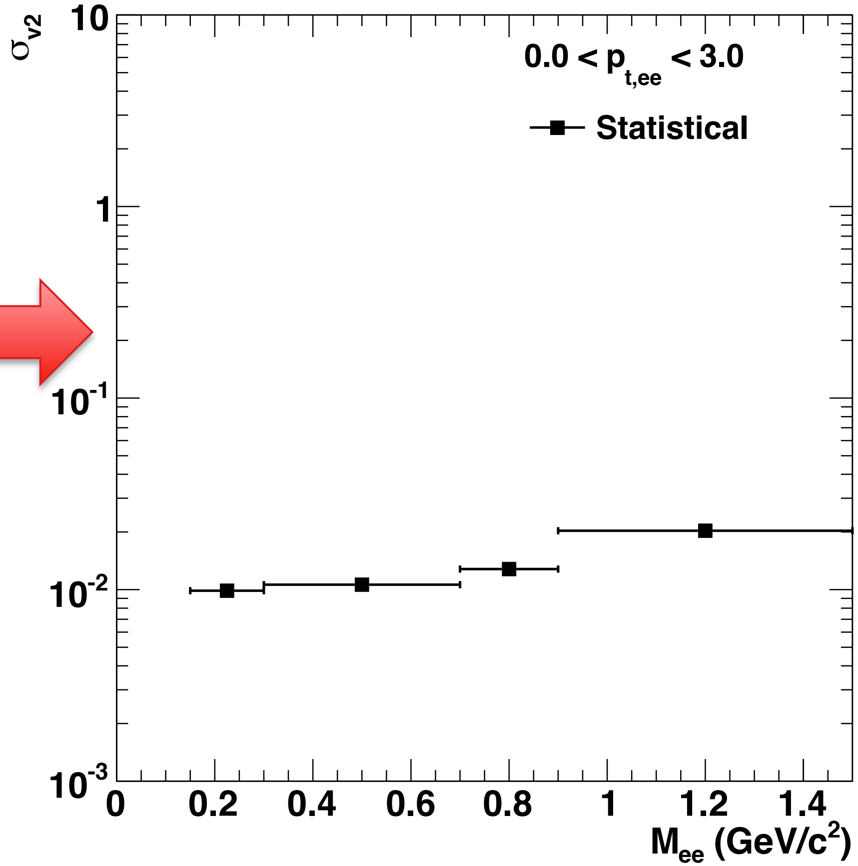
ELLIPTIC FLOW (20-40% CENTRALITY)





- Current ITS
- Current readout

- New ITS: less conversion, better DCA resolution
- New readout: x100 statistics

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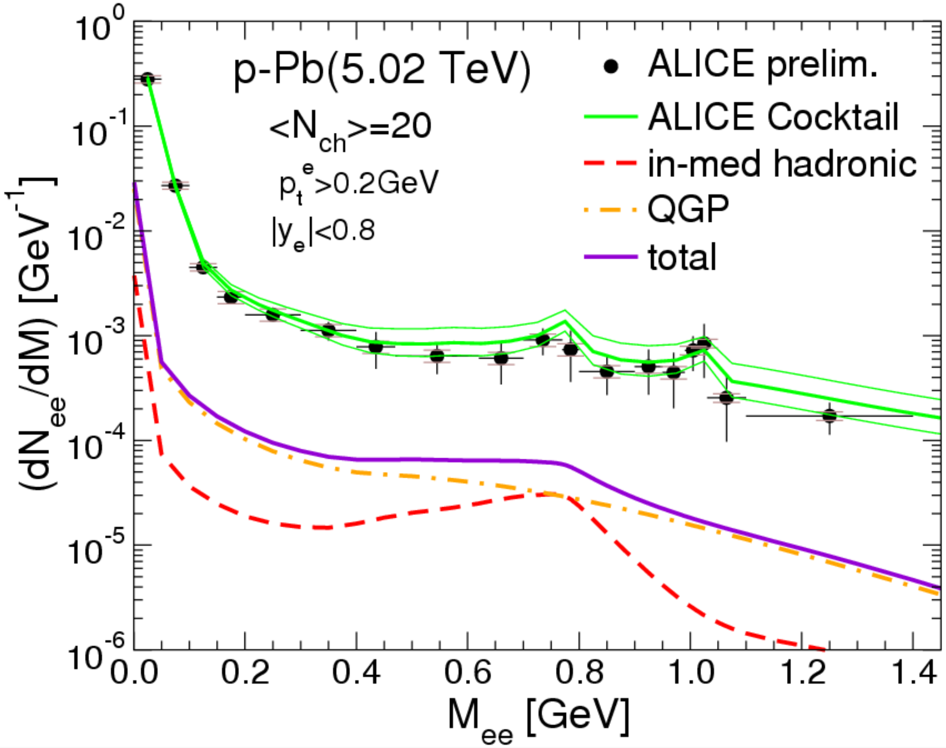
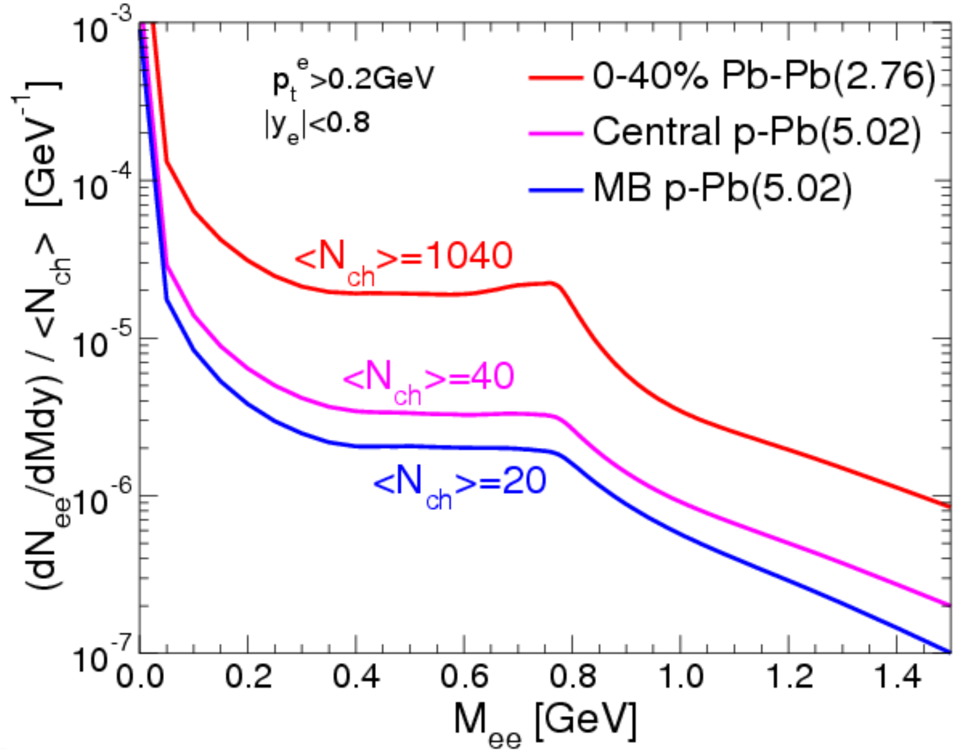
SMALL SYSTEMS

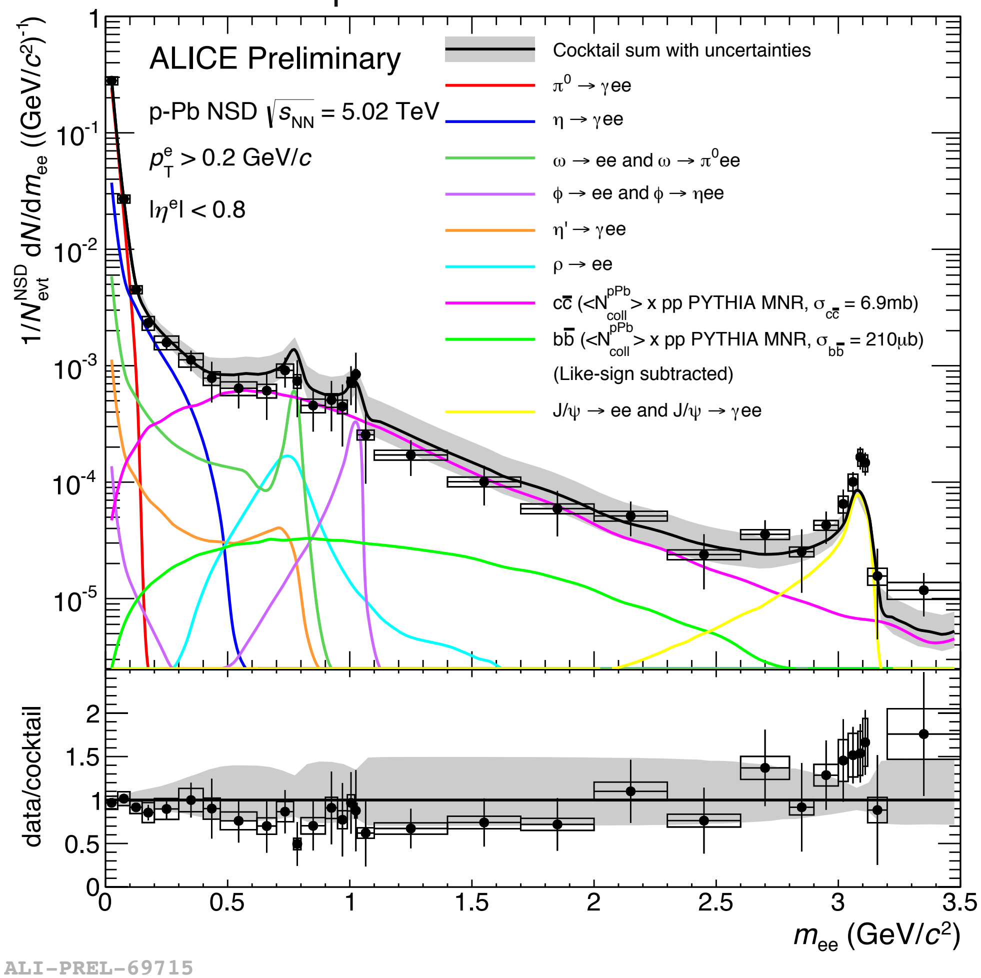




- Thermal radiation in small systems?
- R. Rapp, IS2014:
    - **10% thermal contribution in MB p-Pb collisions**

ESTIMATES FOR RUN 3/4 (p-Pb, 50 nb^{-1})

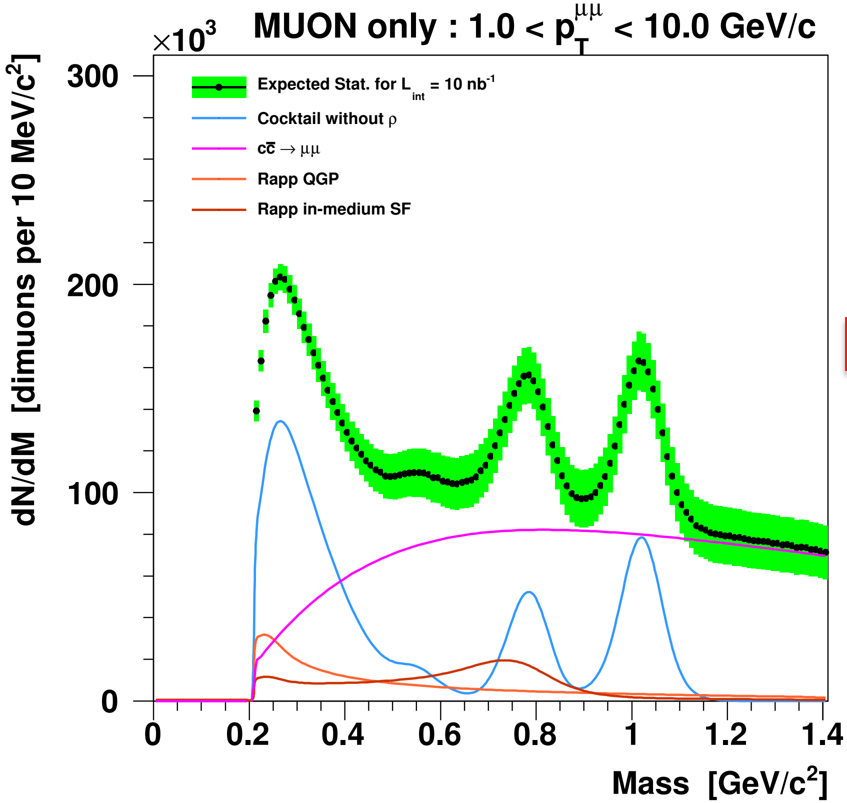
From Run 1 performance:

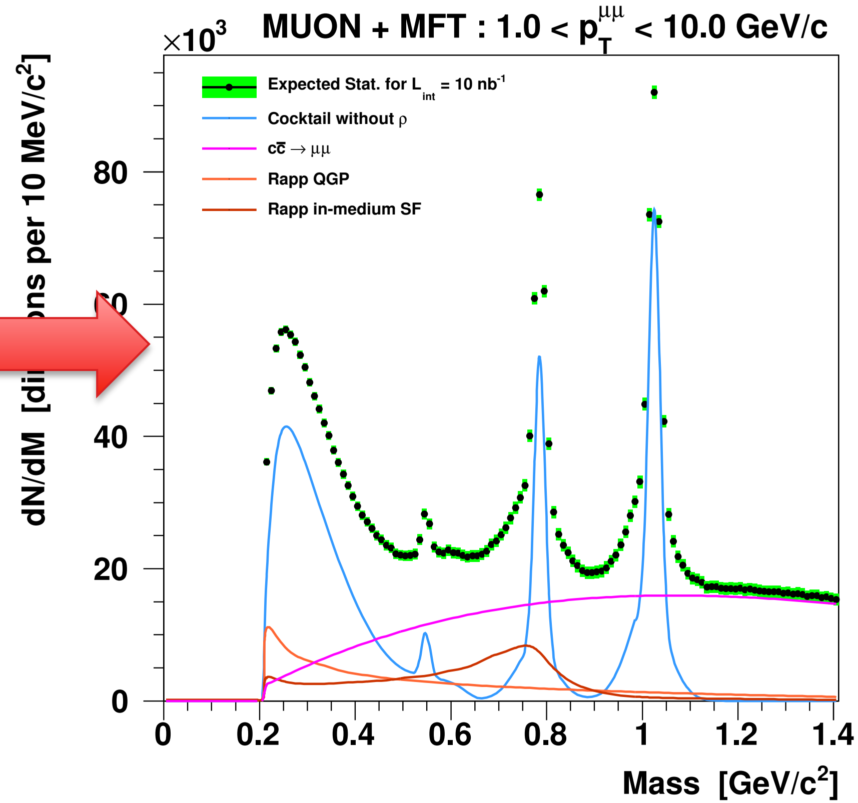


- Run 1 results based on L_{int} ~ 50 μb^{-1}.
- **Stat. uncertainties**
  - In the interesting mass regions (0.3<m_{ee}<0.7 GeV/c^2) and (1<m_{ee}<3 GeV/c^2):
  - **σ_{stat} ~ 20 - 50%**
- **For Run 3/4 (50 nb^{-1})**
  - **σ_{stat} ~ 1 - 2%**
- Measurement will not be limited by stat. uncertainties

LOW MASS DIMUONS

UPGRADE IMPROVEMENT (Pb-Pb)

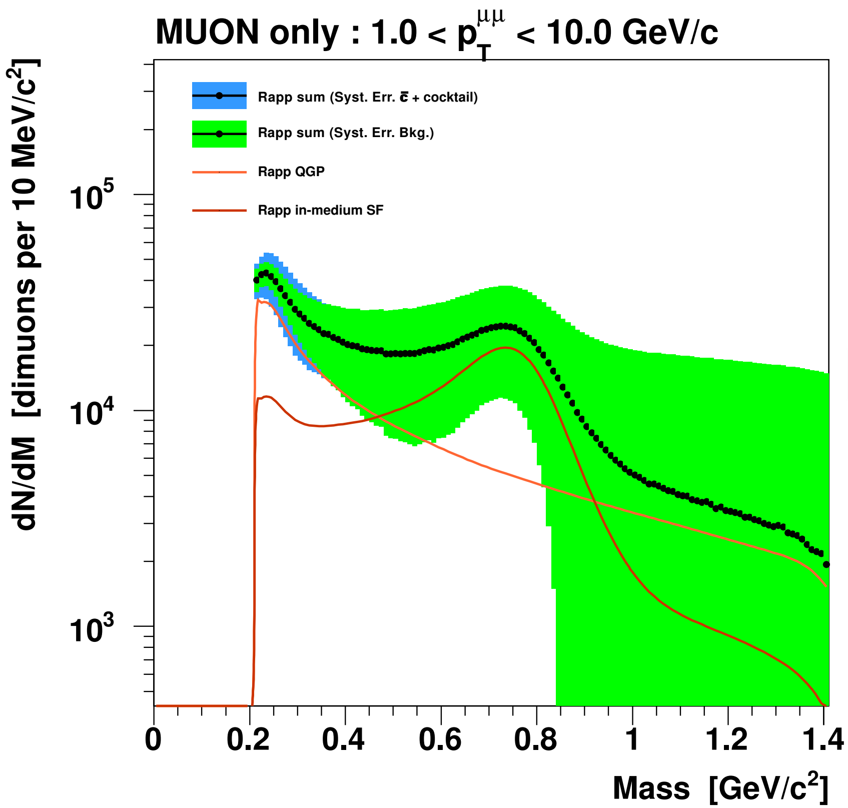


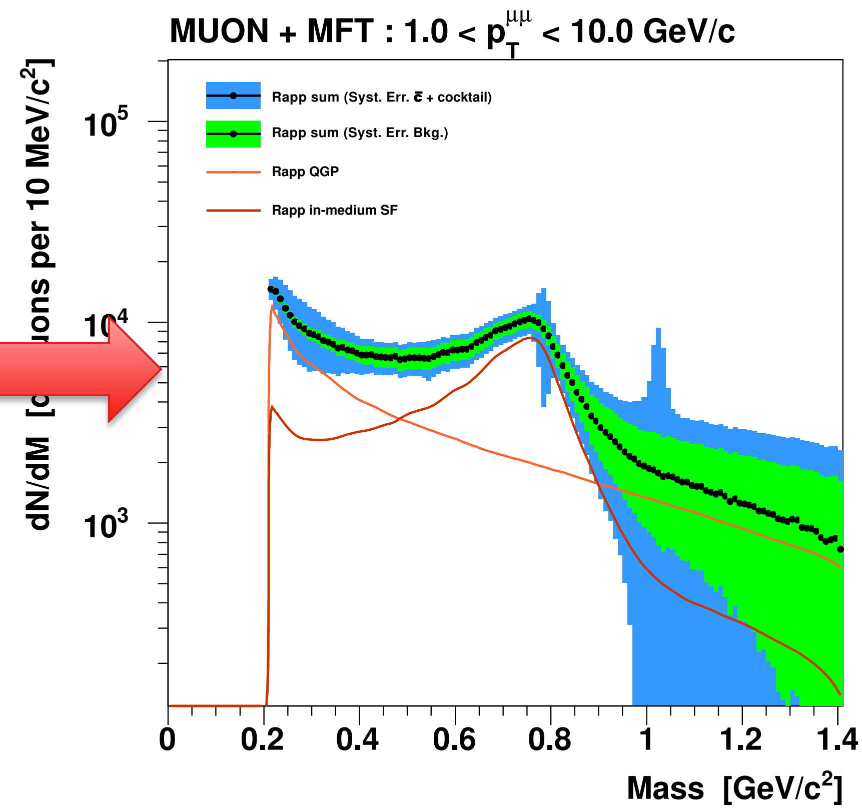


- MUON spectrometer only

- MUON+MFT: better mass resolution, less background

SPECTRAL FUNCTION



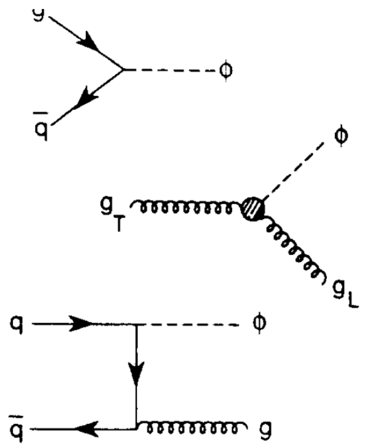


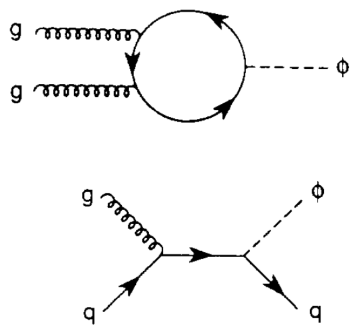
- Low mass spectral function with ~20% uncertainty
- Thermal radiation ($M > 1\mathrm{GeV}/c^2$) difficult

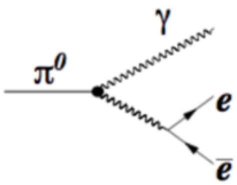
After **subtraction** of **long-lived light- and heavy-flavour sources**

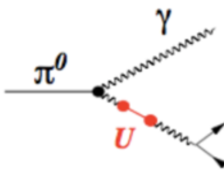
DARK PHOTONS

BEYOND STANDARD MODEL









- **Light scalar or vector BSM bosons** could be observed in **high-energy (with large QGP volumes produced), high-luminosity nuclear collisions** *J. Ellis & P. Salati, Nuclear Physics B342 (1990) J. Davis & C. Böhm, arXiv:1306.3653*

- **Resonance in the thermal dilepton production from the QGP** for masses up to 3 GeV/c^2: dilepton measurements in ALICE could set limits on quark- and lepton-couplings of light BSM bosons

- **ALICE: feasibility studies on dark photons of mass < 100 MeV/c^2**

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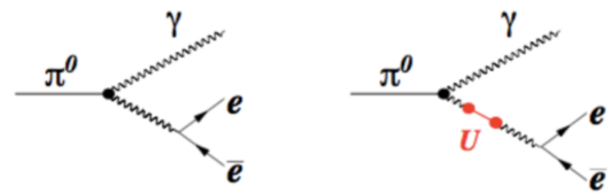
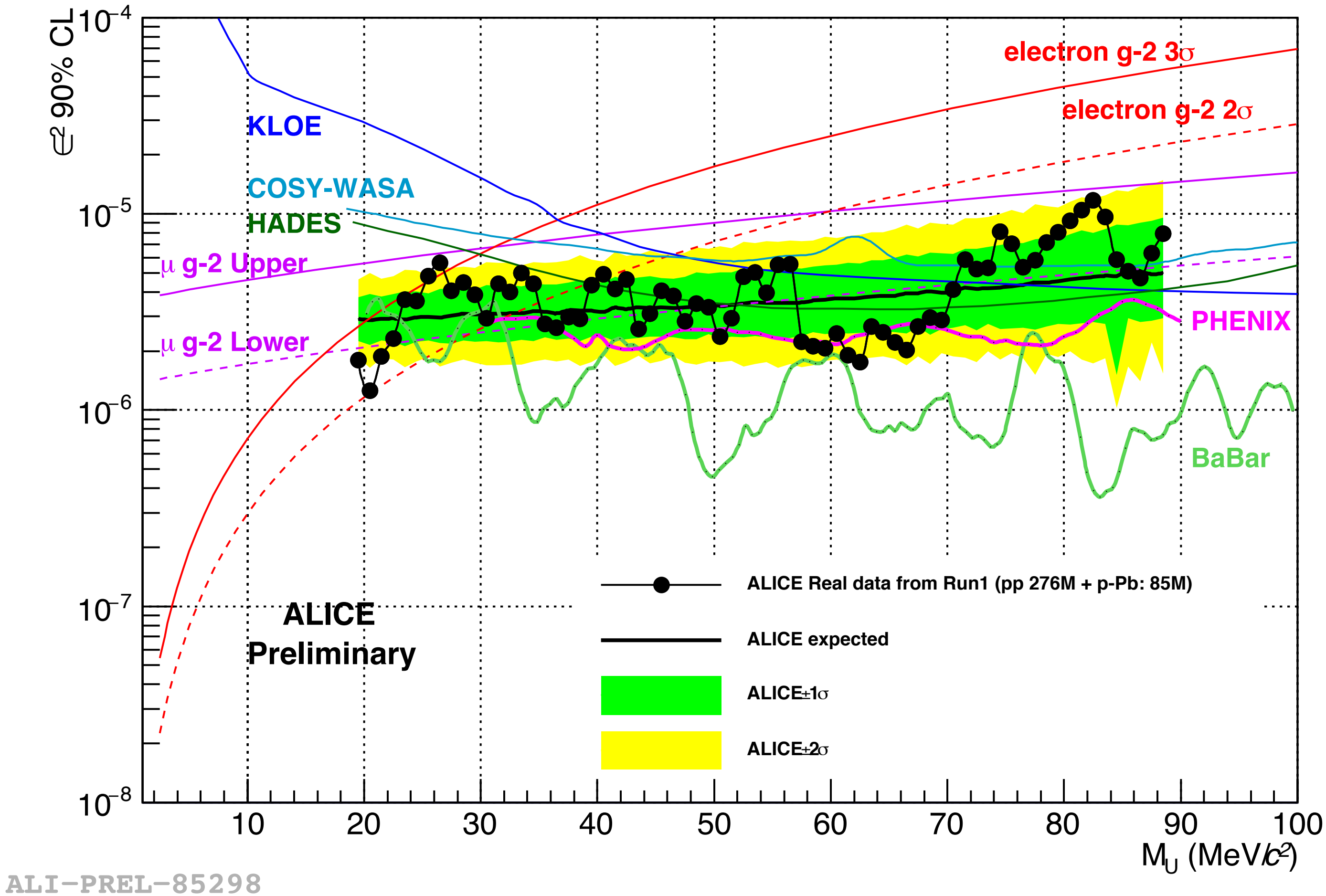
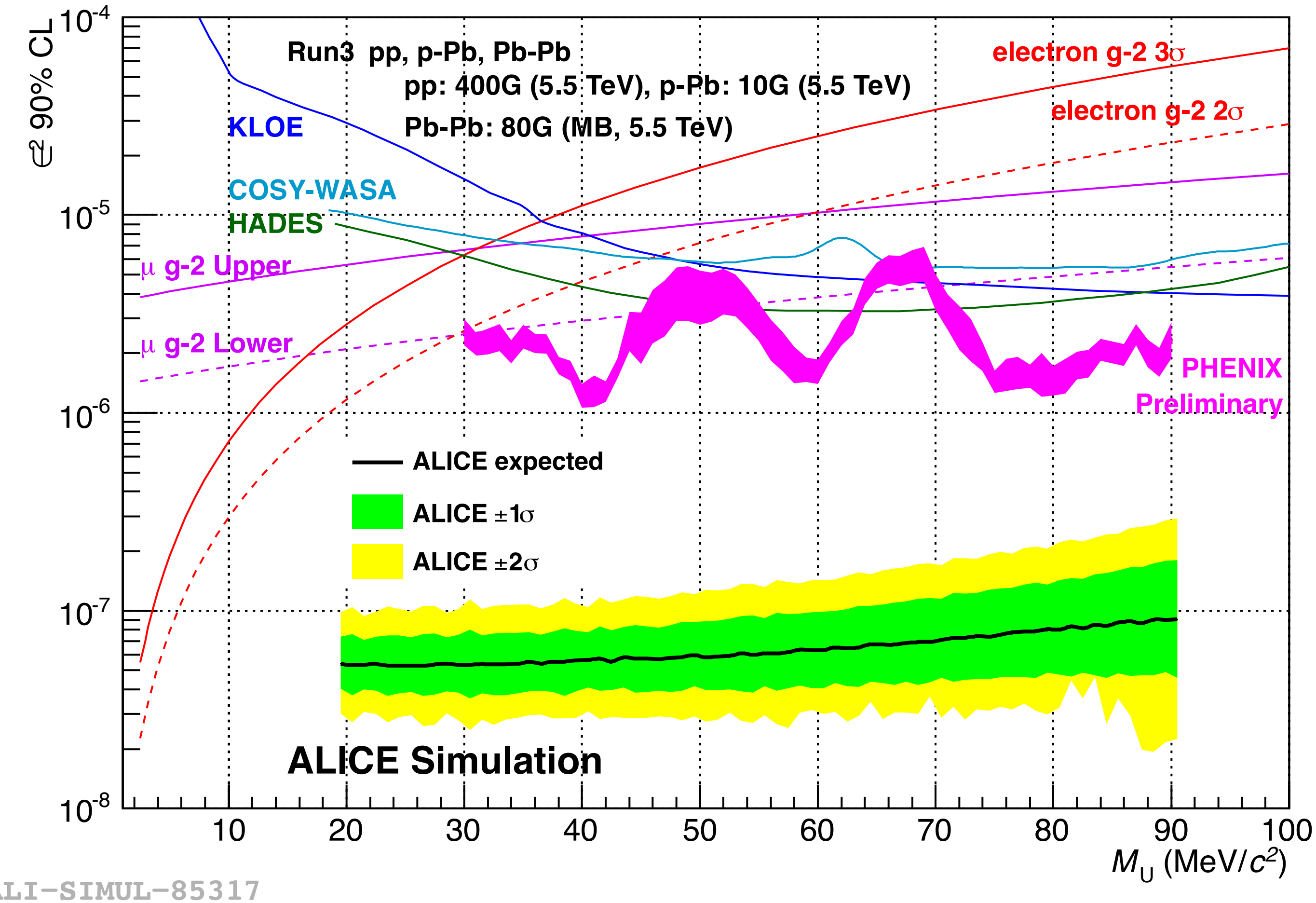
DARK PHOTONS (RUN1)

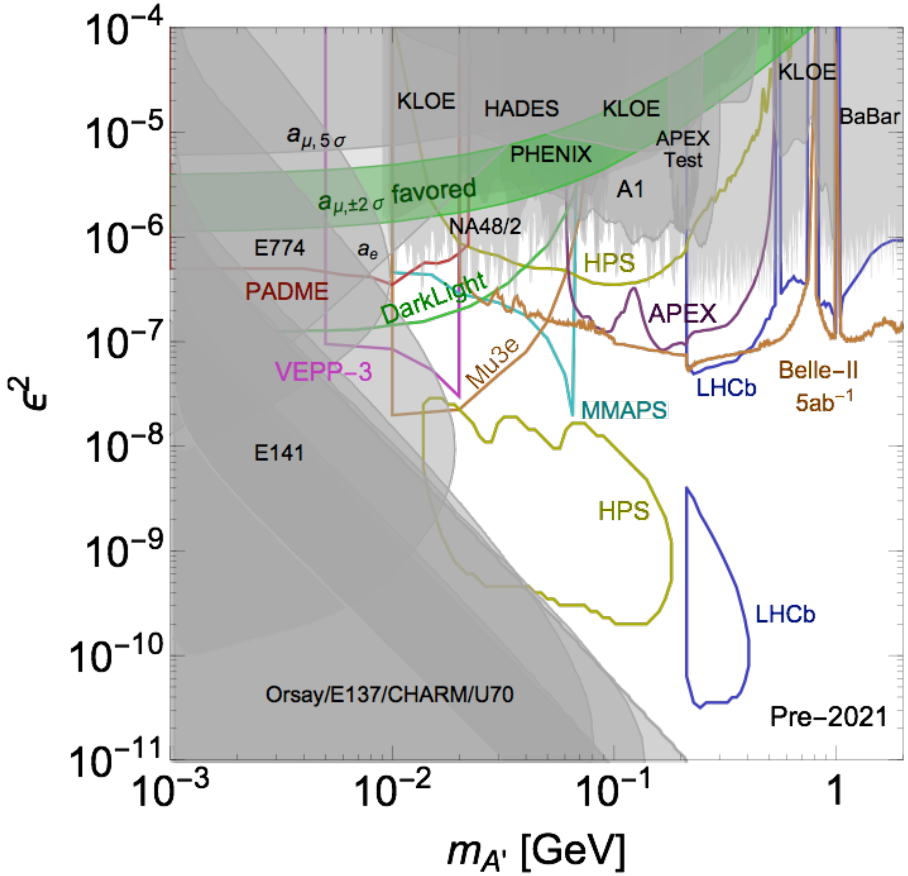


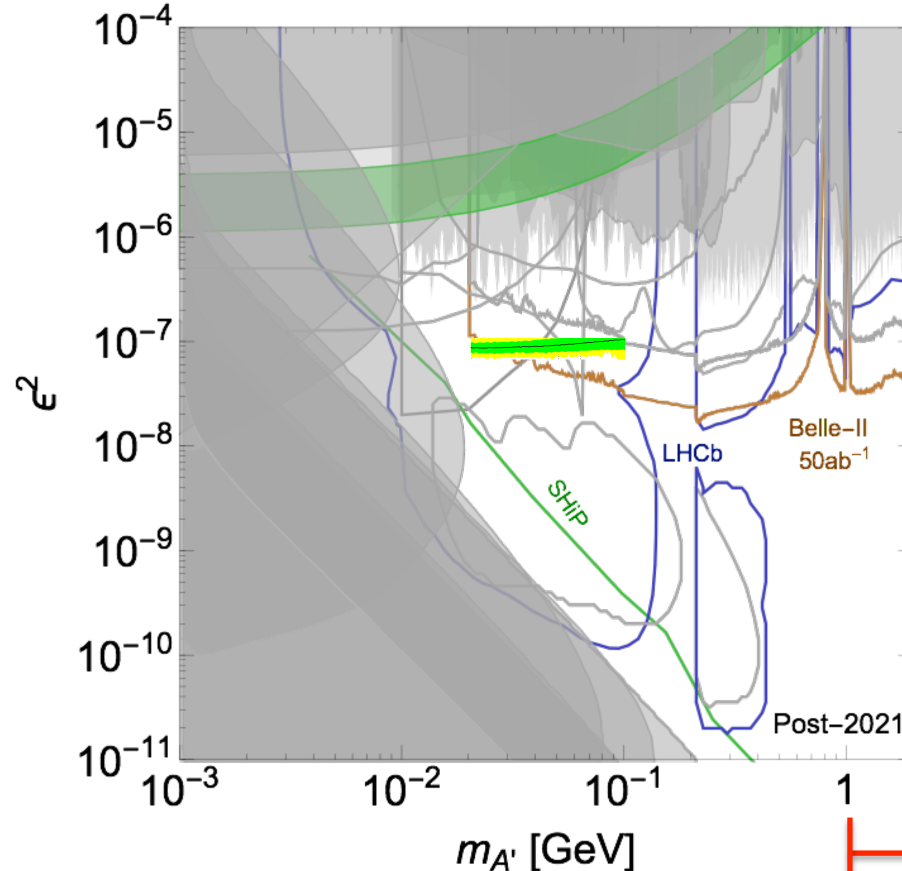


DARK PHOTONS (RUN3)



WORLD DATA + ALICE



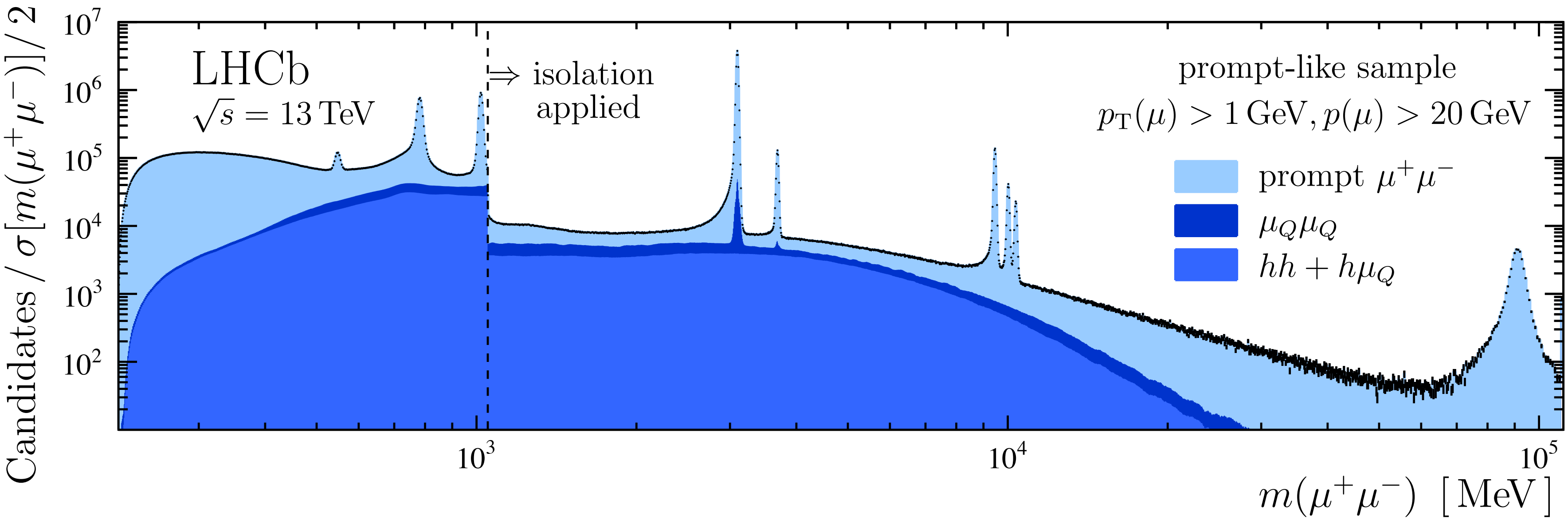


GeV scale?

***J. Davis, C. Boehm**, arXiv:1306.3653*

Dark Sector Community Report 2016
arXiv: 1608.08632

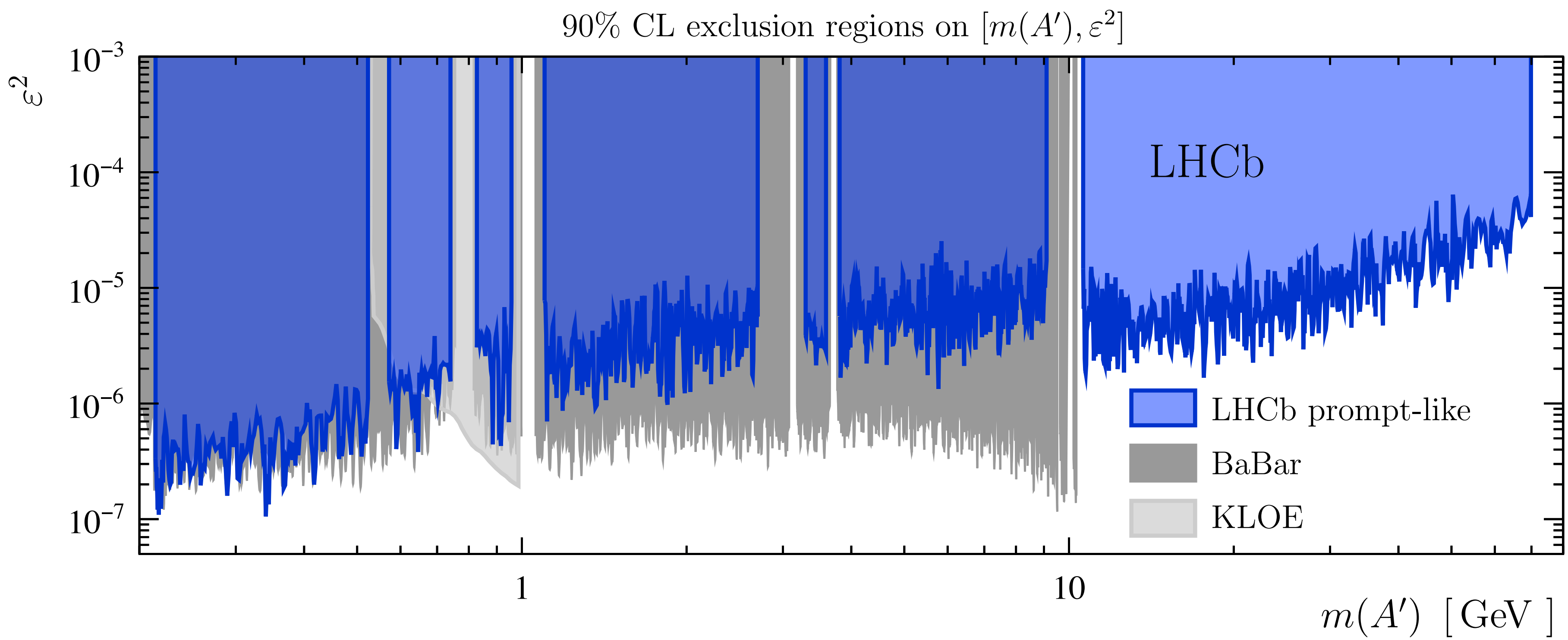
OTHER LHC EXPERIMENTS, e.g. LHCb



- intermediate-mass dileptons: precision temperature measurement above the φ mass via thermal radiation to be checked also in high-multiplicity p-Pb, pp
- masses below to be seen, current minimal p_μ with ID 3 GeV/*c*: p_T = 200, 400 MeV/*c* (η = 4.0, 2.5)

LHCb, arXiv:1710.02867 [hep-ex]

OTHER LHC EXPERIMENTS, e.g. LHCb



- Possibility to measure below 100 MeV?

LHCb, arXiv:1710.02867 [hep-ex]

CONCLUSIONS

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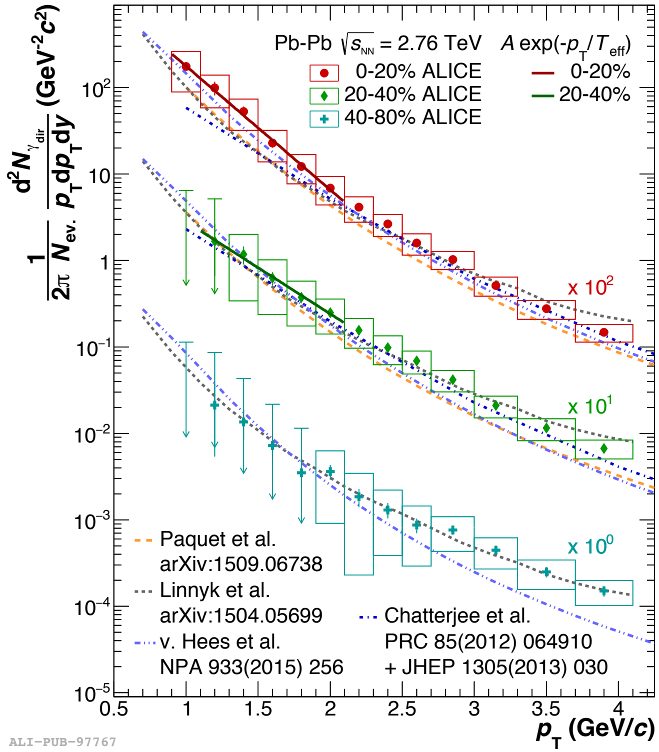
- Low mass dielectrons:

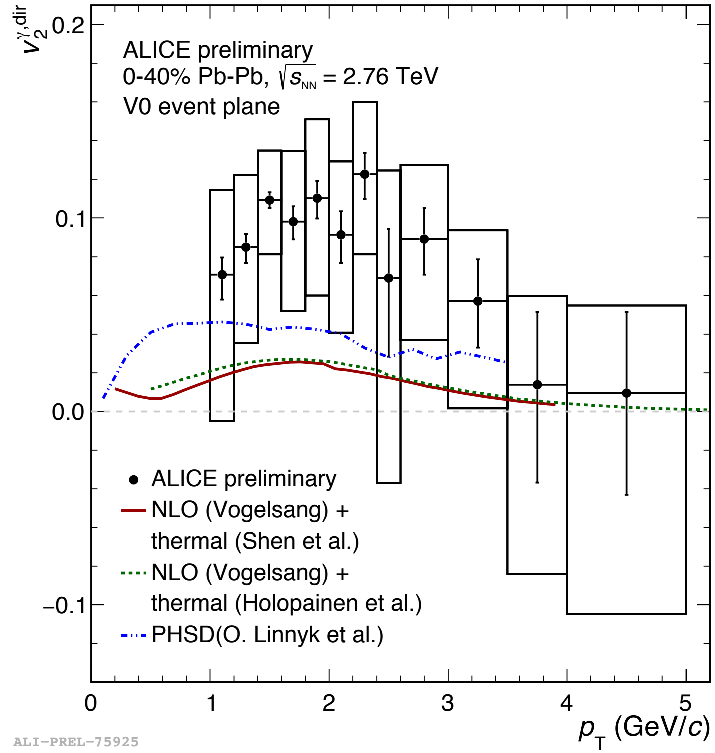
	Statistical uncertainty
Temperature (intermediate mass)	10 %
Elliptic flow ($v_2 = 0.1$) [4]	10 %
Low-mass spectral function [4]	20 %

- Low mass dimuons:
  - Higher statistics (10 nb^{-1}), but higher p_T cut and larger HF background than dielectrons
  - **prompt signals from QGP measurable within 20% uncertainty**
- Small systems:
  - Thermal radiation from high multiplicity pp and p-Pb collisions?
  - **Will not be limited by stat. uncertainties**
- Dark photons:
  - **Sensitivity ε^2~10^{-7} for 20<M_{ee}<90 MeV/c^2**

BACKUP

THERMAL RADIATION (PHOTONS)

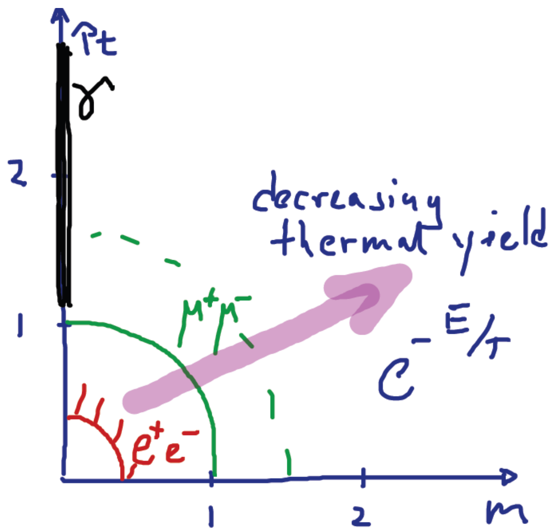




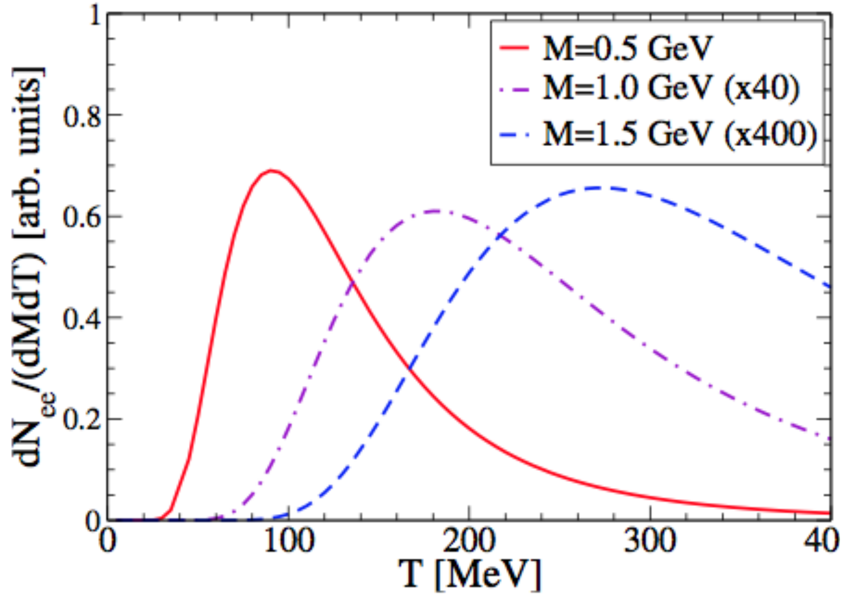
- **Measure thermal radiation** (black body photons)
- First measurement at LHC from soft exponential component of photon p_T spectrum (*ALICE, Phys.Lett. B754 (2016) 235*): ***T* ~ 300 MeV** (effective temperature averaged over system evolution)
- **Direct photon flow** larger than available theory predictions

ALICE

THERMAL RADIATION (DILEPTONS)

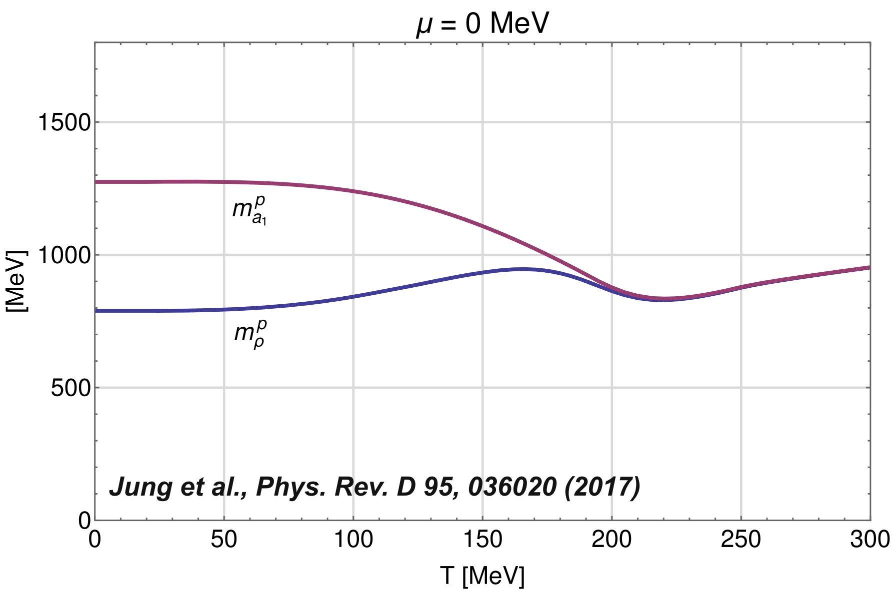


R. Rapp Acta Phys.Polon. B42 (2011)

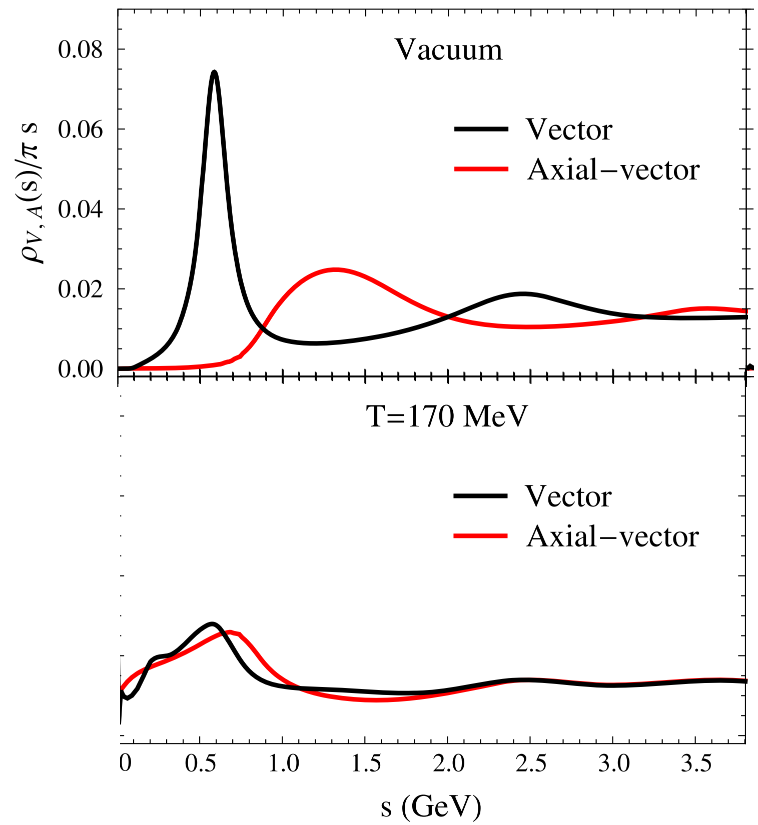


- **Measure thermal radiation** (black body photons)
- First measurement at LHC from soft exponential component of photon p_T spectrum (*ALICE, Phys.Lett. B754 (2016) 235*): ***T* ~ 300 MeV** (effective temperature averaged over system evolution)
- Dileptons:
  - **Map temperature during system evolution**
  - Invariant mass method **not sensitive to "blue-shift" from radial flow**

CHIRAL SYMMETRY AND SPECTRAL FUNCTION

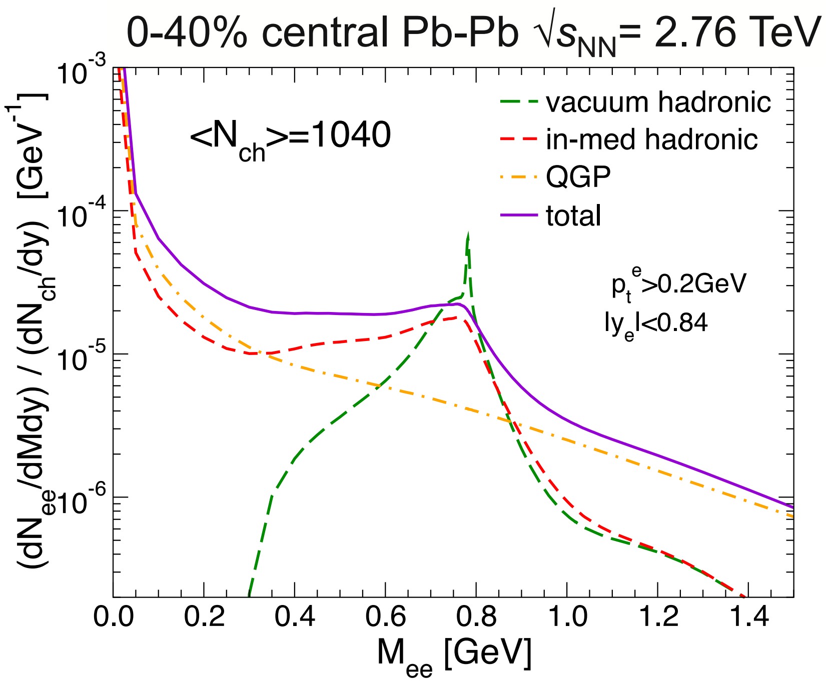


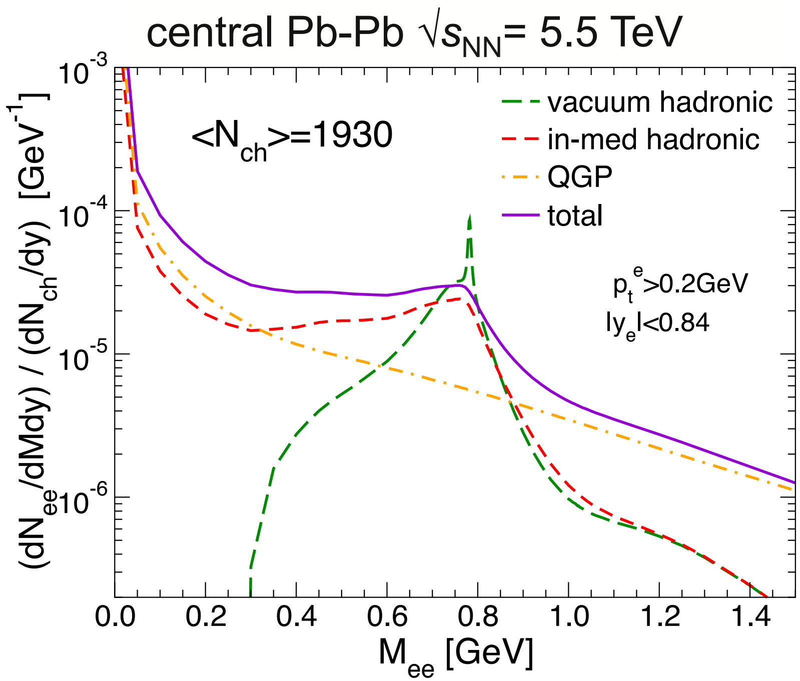
Hohler, Rapp, Physics Letters B 731 (2014) 103–109



symmetry	$SU_V(2)$	$SU_A(2)$
vacuum	unbroken	broken
high temperature	unbroken	unbroken
multiplets	$(n, p), \ldots$	$(\sigma, \pi), (\rho, a_1), \ldots$
order parameter	—	$\langle \bar{q}q \rangle$
	"Isospin"	"Parity"

INVARIANT MASS SPECTRA





At LHC energies:

- Vanishing μ_B: direct comparability to Lattice QCD
- Sizeable in-medium modification of ρ
- Large thermal radiation contribution above 1 GeV/c^2

R. Rapp, arXiv:1304.2309 [hep-ph]

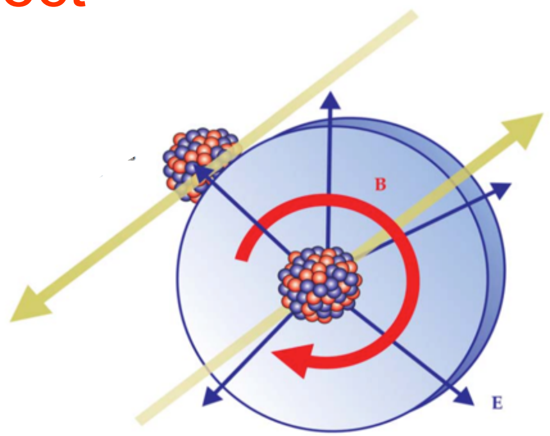
ALICE AFTER 2020

- Improved **vertex resolution**
  - Better separation of electrons from charm and bottom decays
- **Reduced material budget** and improved **low p_T efficiency**
  - Smaller background from conversion electrons
- Dedicated **low B field** run
  - Recover low p_T tracks
  - 3 nb^{-1} at B = 0.2 T
- **Higher rate** capability
  - 50 kHz Pb-Pb
- Muon forward tracker (MFT) in addition to muon spectrometer
  - **Improved mass resolution**
  - **Reduced background**

Production of low p_T e^+e^- pairs in peripheral collisions at HL-LHC

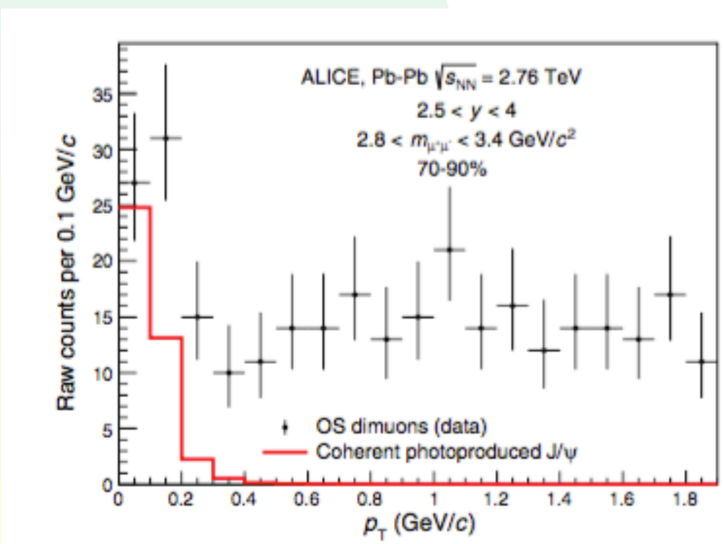
Spencer Klein, LBNL

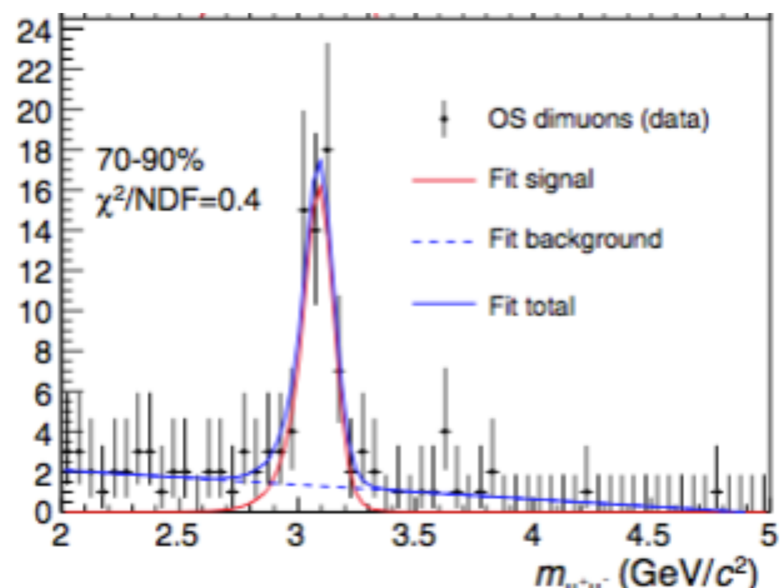
- Ultra-peripheral collisions tell us what to expect
  - Photons ala Weizsacker-Williams
    - Crossed E and B fields
  - Coherent $J/\psi \rightarrow ee$ photoproduction
    - Peaked at M_{ee}= J/ψ mass
  - $\gamma\gamma$ -> ee
    - Broadband emission, peaked at low M_{ee}
    - Individual lepton rapidity distribution is very very broad
      - Cross-section is very large, but mostly invisible in central detectors
      - Individual lepton p_T spectrum must softer than from J/ψ
  - Both have emission peaked with pair p_T < 100 MeV/c
    - Two mechanisms, but surprisingly similar pair p_T spectra
- What can we learn from these reactions?



ALICE J/ψ –> $\mu^+\mu^-$ excess

- J/ψ excess for pT < 100 MeV/c in peripheral collisions
  - Magnitude is significant 70-90% centrality larger R_{AA}
- Low p_T peak not expected for any hadronic mechanism
  - Consistent with coherent photoproduction
- Seen at forward rapidity, 2.5 y < 4

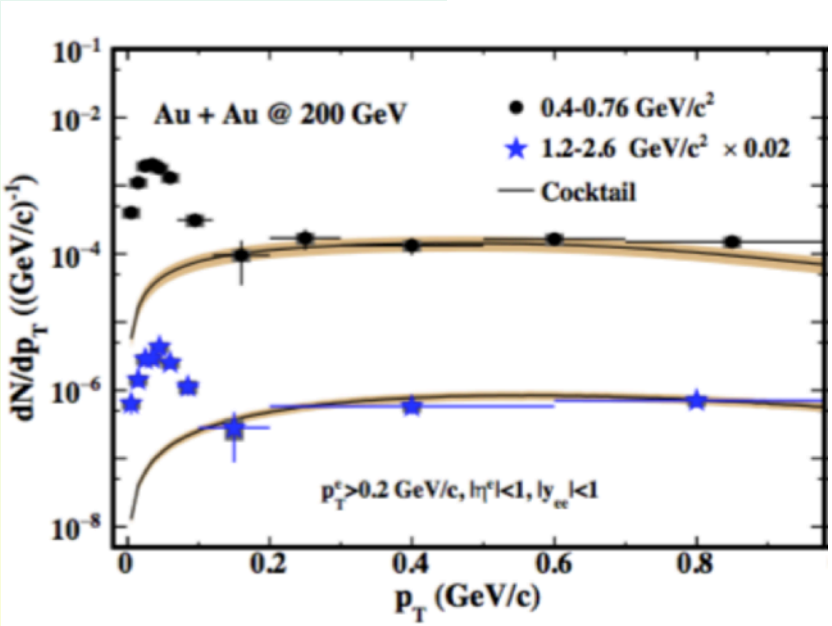


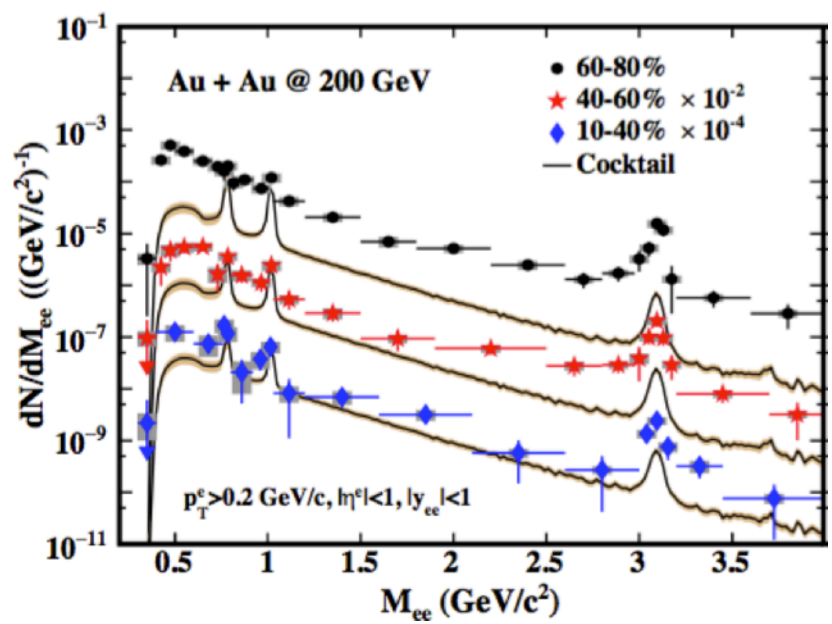


ALICE, PRL 116, 222301 (2016)

STAR low p_T e^+e^- excess in AuAu & UU

- Excess over hadronic cocktail for p_T < 150 MeV/c
- p_T spectrum similar to ALICE
- Mass spectrum peaked at J/ψ, but continuum also visible.
  - Continuum not seen by ALICE
    - ALICE FMS imposes $p_{T,\text{single}\,\mu}$ > 1 Gev/c

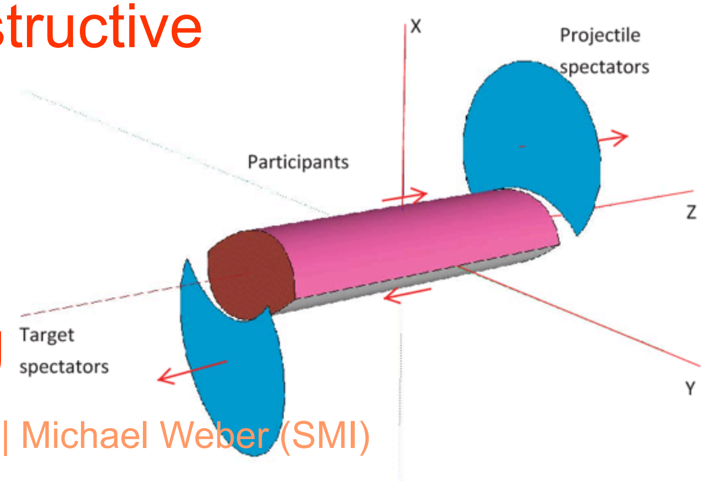




S. Yang [STAR], QM17

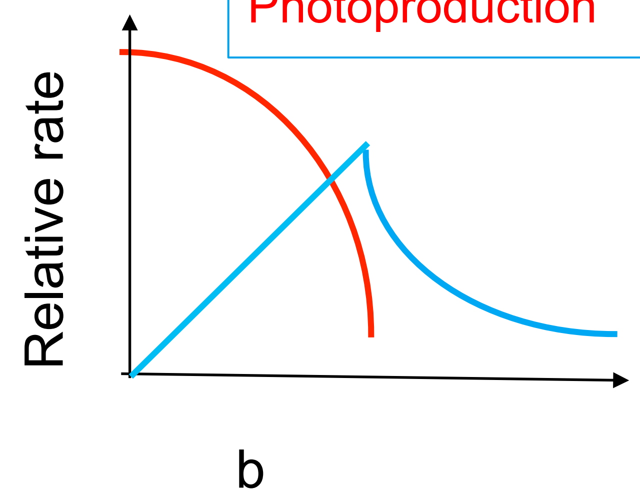
Photoproduction cross-section in PCs

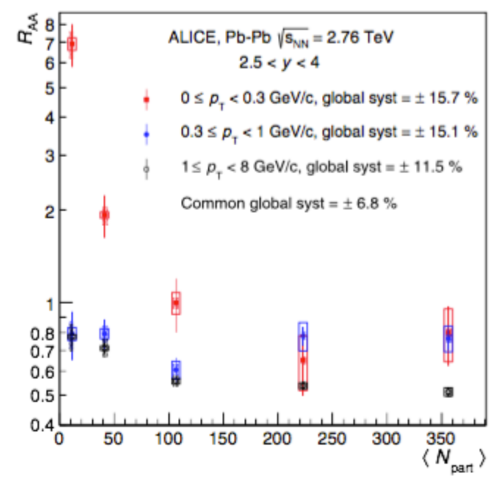
- σ depends on coherence for photon emission and in the target
  - Entire target, or just spectator region?
- Photons are emitted before collision, at retarded time $t \sim k/\gamma$
  - They come from the whole nucleus
- Participant nucleons may lose energy via hadronic interaction, before or after the photoproduction interaction
  - If they lose energy first, $\sigma(\gamma p \to J/\psi\ p)$ drops
    - Time ordering matters – consider diagrams with both possibilities
- Photon flux striking participant nucleons is lower (Gauss' law)
- Participants are at very small |b|, so destructive interference reduces the cross-section
  - Small contribution to cross-section
- J/ψ produced just outside the reaction zone should be destroyed by expanding fireball.



R_{AA} for photonic interactions

- R_{AA} not optimum term
  - Different production mechanisms have different scaling
    - γγ -> ee scales as Z^4
    - γA -> J/ψ A scales as Z^2A^2
- Photon flux is highest around nuclear periphery
- Photoproduction is largest in the most peripheral collisions
  - Drops sharply with decreasing radii
  - Drops more slowly with increasing radii
  - γγ-> ee has fairly little |b| dependence
- R_{AA} varies rapidly with centrality

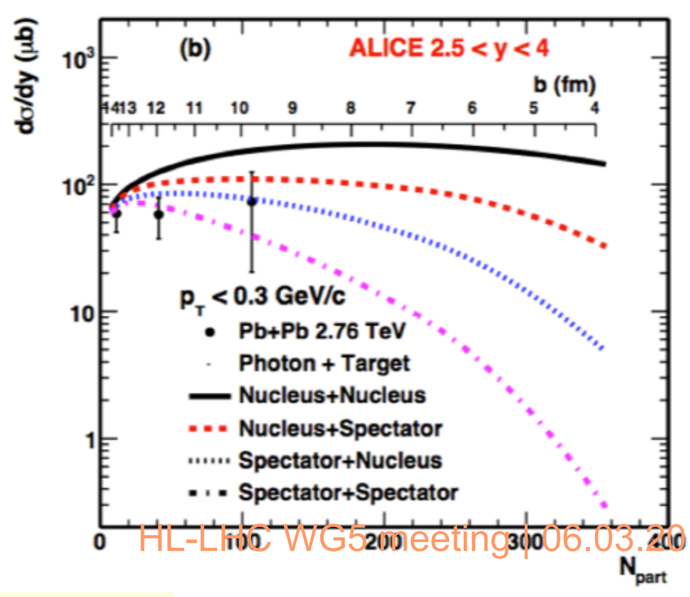




ALICE, PRL 116, 222301 (2016)

σ For J/ψ photoproduction

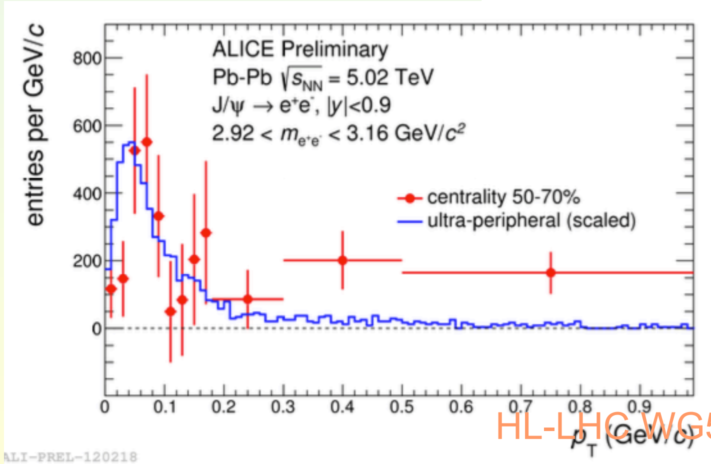
- Four possibilities:
  - photon emission from the whole nucleus or spectators only
  - Targets: whole nucleus, or just spectators
- Should bracket the actual cross-section
  - Photon emission from nucleus expected
- Predictions consistent with STAR & ALICE data
  - "Nucleus+Nucleus," " Spectator+Spectator" slightly disfavored

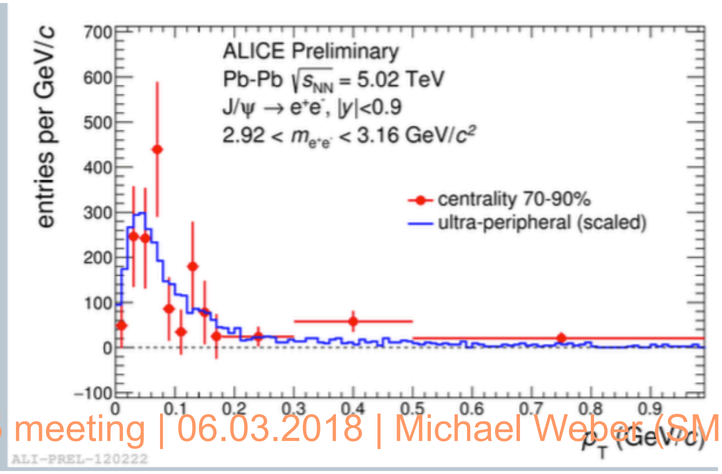


W. Zha et al. (SK), arXiv:1705.01460

p_T spectrum for $\gamma A \to J/\psi$ in PCs

- Spectrum is consistent with UPC J/ψ photoproduction data
  - Drop at low p_T due to interference between two directions
    - Smaller |b|, so interference extends to higher p_T than for UPCs
    - Could reduce total cross-section
- Spectator-only target has a different matter distribution than full nucleus target.
  - Different p_T spectrum + some azimuthal anisotropy
- p_T spectrum depends on size of the coherence region

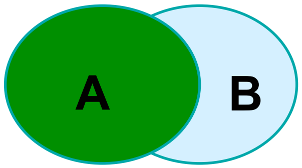




Z. Zhou [ALICE], QM17

What can we learn about hadronic collisions?

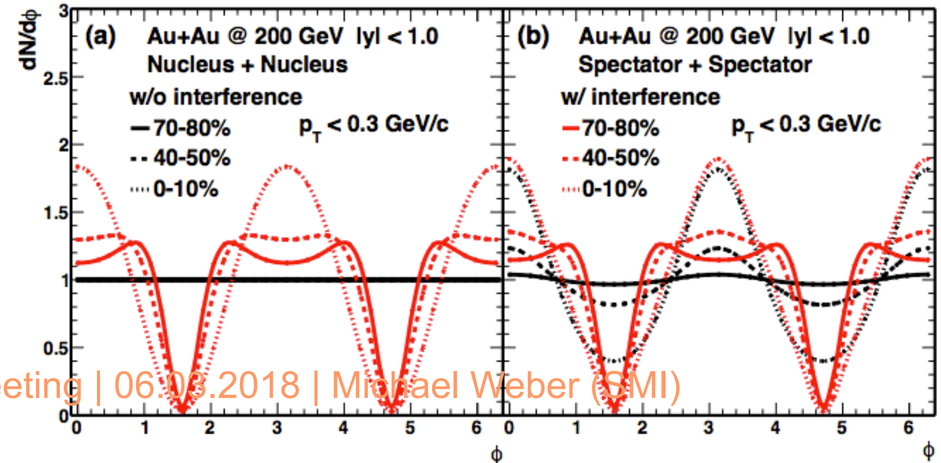
- Most of J/ψ photoproduction amplitude is from spectator region
  - Expanding plasma might destroy long-lived (10-20 s) J/ψ
    - Rate measurement is interesting, but more precise measurements, theory needed!
- J/ψ p_T angular distribution is Fourier transform of coherent production region
  - I. e. region A minus region B



- The azimuthal distribution is sensitive to the event plane

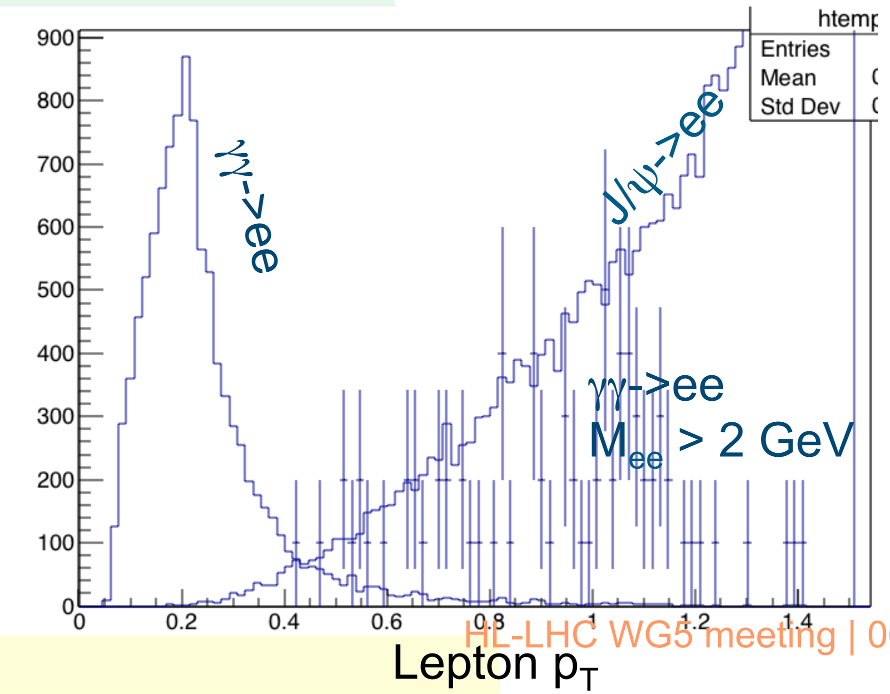
W. Zha et al. (SK), arXiv:1705.01460

Z. Xu (Pers. Comm.)



Single-lepton p_T distributions

- J/ψ (or ρ/ω/ϕ) -> ee and γγ-> ee share many characteristics
  - Similar pair p_T spectra
  - Hard to distinguish rapidity distributions in central detectors
- The angular distribution of the final state l^+l^- is very different
  - -> Very different lepton rapidity and p_T distributions
  - With $p_{T\mu}$ > 1 GeV/c cut, ALICE sees J/ψ -> ee only



Lepton p_T w/ STAR cuts
STAR γγ-> ee
STAR J/ψ -> ee
STAR γγ->ee w/ M_{ee} > 2 GeV/c
J/ψ are in UPC, but this doesn't affect lepton spectra much

Arbitrary normalization

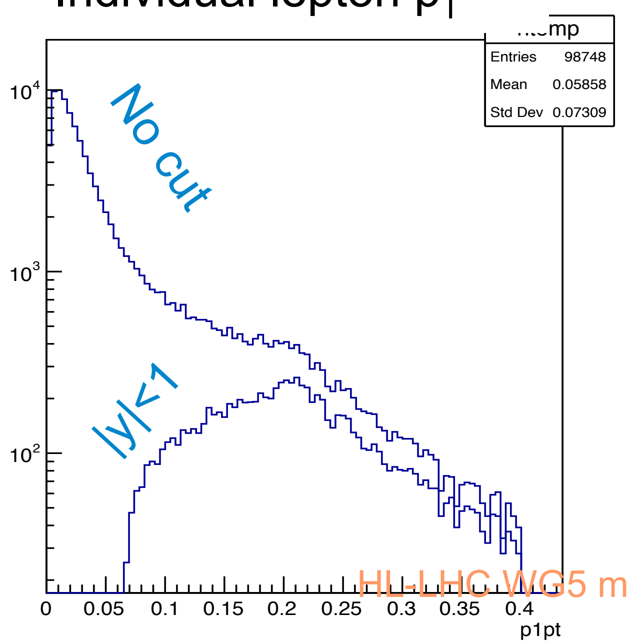
Conclusions

- STAR and ALICE have observed an excess of dilepton pairs with p_T < ~ 100 MeV/c in peripheral heavy ion collisions
  - STAR sees J/ψ + a mass continuum
  - ALICE sees only J/ψ
- The rate and kinematics are consistent with expectations from coherent photoproduction and $\gamma\gamma \rightarrow l^+l^-$
- HL-LHC will collect samples 140 times larger than the current ALICE measurement.
  - The J/ψ rate and cross-section are sensitive to the size of the production region, and the possible destruction of spectator-region J/ψ by the expanding fireball.
  - The J/ψ p_T distribution might be used to provide an independent determination of the reaction plane, allowing for cross-checks with other methods.
  - More theoretical work is needed to fully benefit from this data.

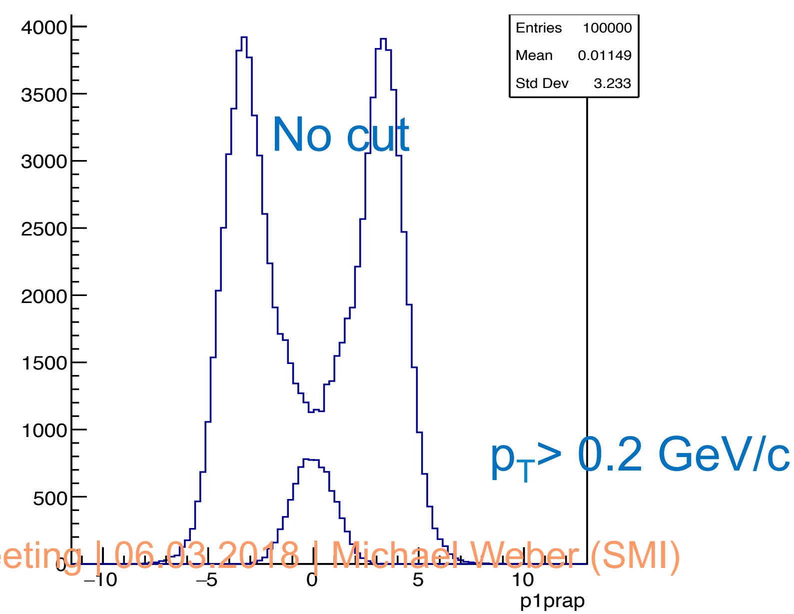
Individual track p_T & pseudorapidity

- Rapidity is heavily forward/backward peaked
  - Moderated by cut p_T track > 0.2 GeV/c
- p_T is peaked near 0
  - After cut |y|<1, <p_T> 0.2 GeV/c
- Very few leptons with p_T > 1 GeV/c → ALICE sees no continuum signal

Individual lepton p_T

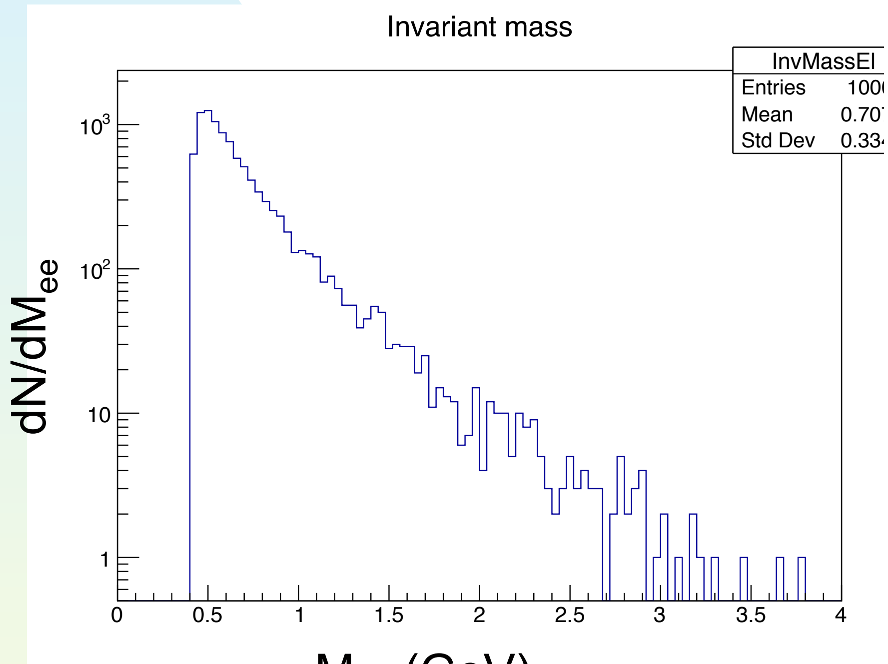


Individual lepton pseudorapidity



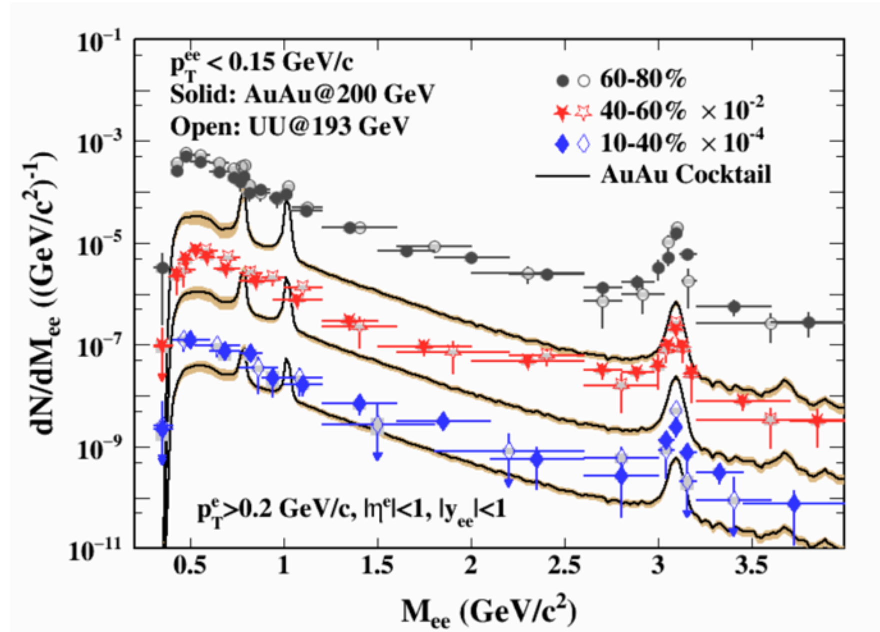
M_{ee} spectrum

STARlight



M_{ee} (GeV)

STAR data

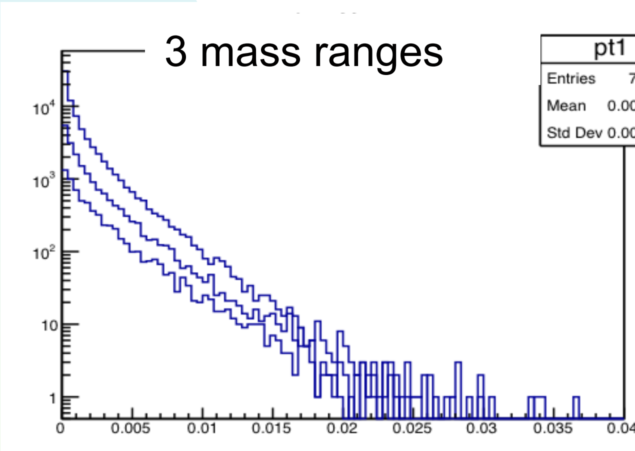


Low p_{Tee} paper did not make a fit to the mass spectrum & the right-hand plot is hard to read

Both decrease about a factor of 10 going from M_{ee}=0.5 GeV to M_{ee}=1.0 GeV & from M_{ee}=1.0 GeV to M_{ee}=2.0 GeV

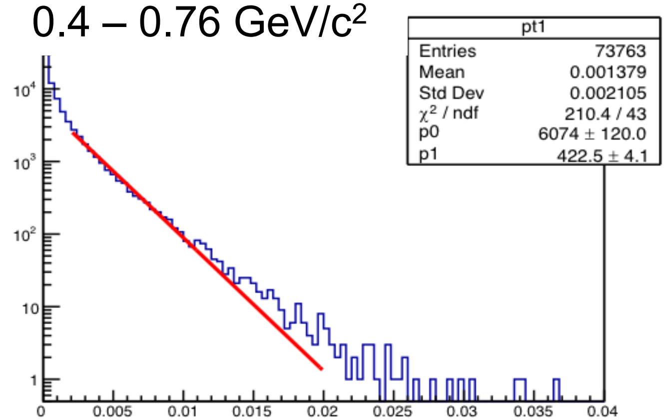
Pair p_T^2

- Histogram p_T^2 in 3 mass bins, ala STAR
  - Fit $0.002 < p_T^2 < 0.02$ $(GeV/c)^2$ range to $dN/dp_T^2 = A \exp(-Bp_T^2)$
    - Not a good fit to the data, but follows STAR procedure
    - Same slope (B) trend as STAR data

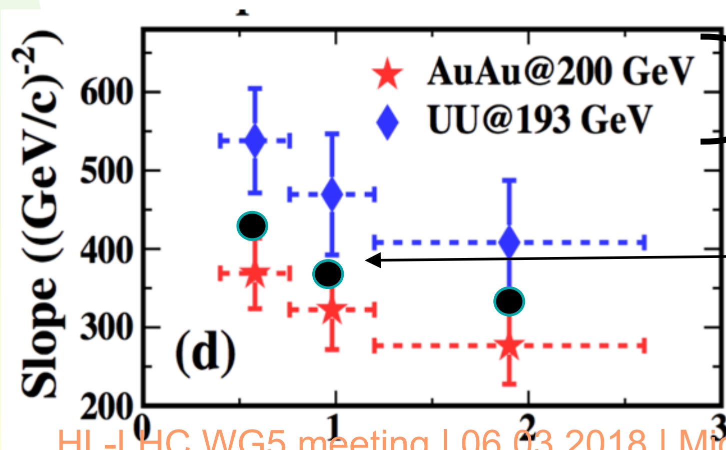


p_T^2 (GeV^2)

0.4 – 0.76 GeV/c^2



p_T^2 (GeV^2)



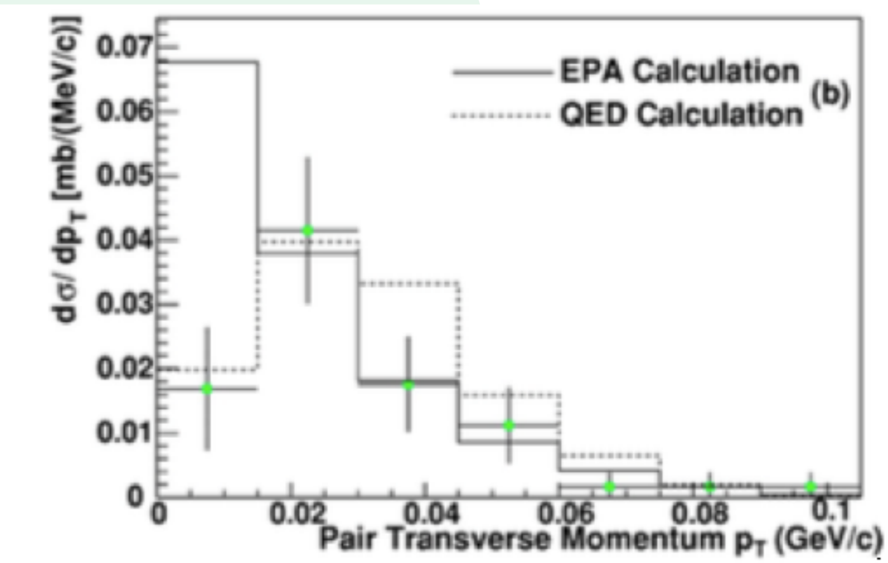
Preliminary STAR data

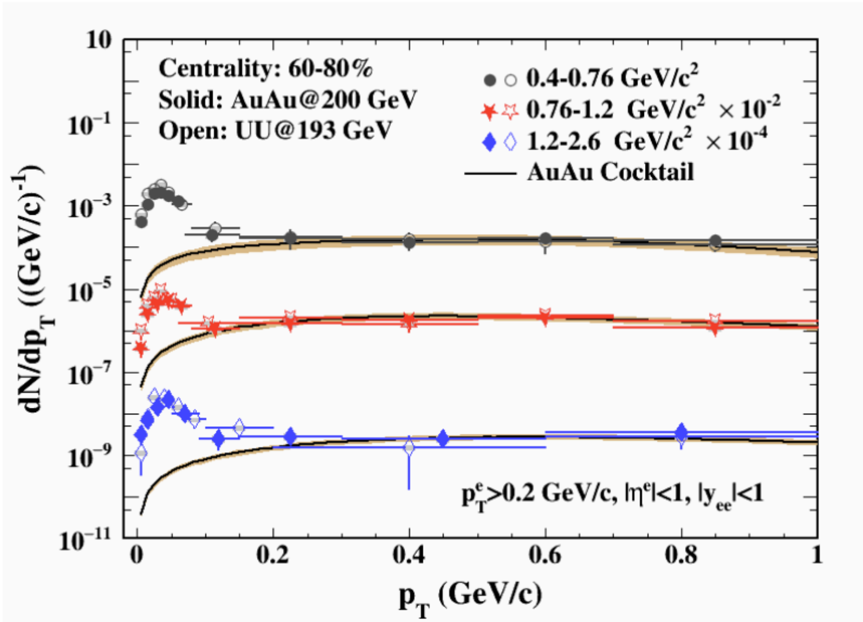
Fits to STARlight Distributions for AuAu

M_{ee} (GeV/c^2)

The low p_T drop

- The STAR p_{Tee} spectrum drops for p_{Tee} < 40 MeV/c
  - Looks similar to interference dip in vector meson photoproduction
- Photon emission with p_T < photon energy/ion Lorentz boost is suppressed
  - Dip width should scale with photon energy, i. e. with M_{ee}
    - Scaling from previous STAR result p_T peak @ 25 MeV -> p_T peak @ 75 MeV/c – reasonably close





STAR: Phys. Rev. C70, 013902 (2004) & S. Yang, QM '17