Dilepton physics opportunities at the LHC

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Student day at EMMI Workshop New Vistas in Photon Physics in Heavy-Ion Collisions
Krakow - 19.09.2022

FSP ALICE
Erforschung von
Universum und Materie

EMMI

GOETHE
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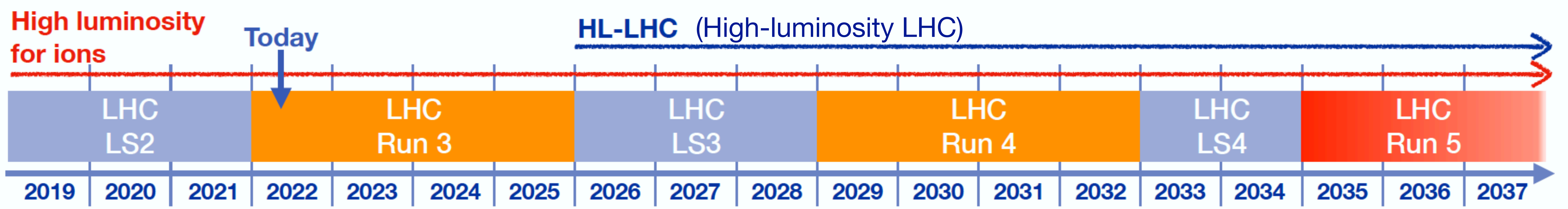
Dilepton physics opportunities at the LHC

- **Introduction**
- **Focus 1: electromagnetic radiation**
- **Focus 2: two-photon interactions**
- **Focus 3: dark photons**

See talk of Jochen Klein at QM2022

Today at the LHC



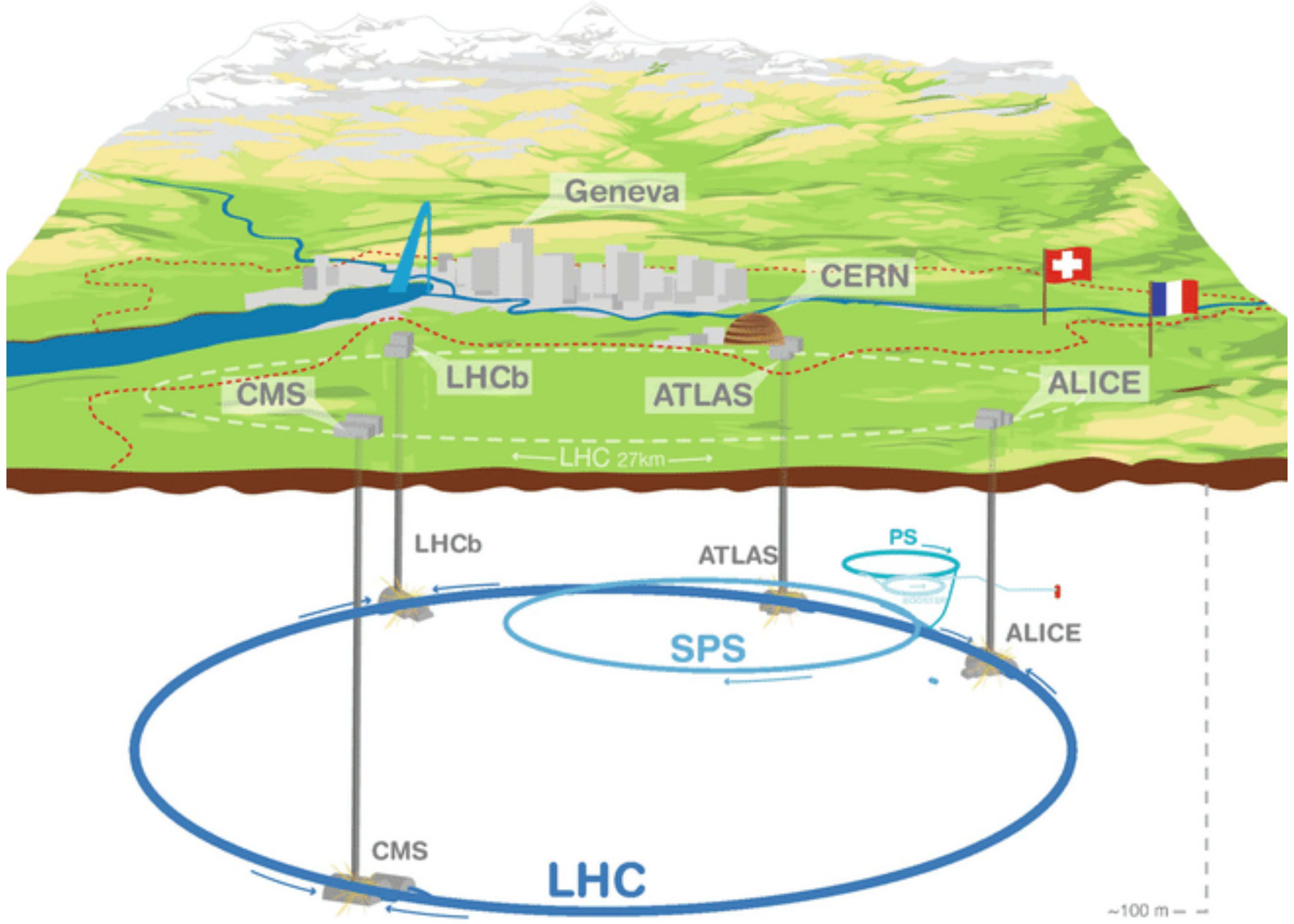
Finalisation of Run 2 analysis

LHC on the verge of high-luminosity era

- $L_{int} \approx 13$ nb^{-1} of Pb—Pb collisions for Run 3 + 4
- About x5 larger instantaneous pp luminosity starting from Run 4

Upgrades of the LHC experiments

- Installed in Long Shutdown 2 (LS2)
- Planned for LS 3 and LS 4



See talk of Jochen Klein at QM2022

LHC schedule

High luminosity for ions — HL-LHC — Higher luminosities for ions

Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		

Collision systems

Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
pp, pPb, Pb—Pb	pp, pPb Xe—Xe, Pb—Pb	pp, pO, OO pPb, Pb—Pb	pp, pPb Pb—Pb	pp, pA?, AA	pp, pA?, AA

Pb—Pb luminosity limited by LHC
up to $1-2\times10^{27}$ cm^{-2}s^{-1}

Run 5 → higher luminosities for ions
- Larger gain for lighter species

Run 4 → HL-LHC
- Push pp luminosity to $\approx 4\times10^{34}$ cm^{-2}s^{-1}

Run 3 → high luminosity for ions ($\approx 7\times10^{27}$ cm^{-2}s^{-1}) **and OO**
- Improved collimation systems
- Ion luminosities now limited by bunch intensities from injectors

See talk of Jochen Klein at QM2022

LHC experiments

High luminosity for ions

HL-LHC

Higher luminosities for ions

Run 1 2009 - 2013

Run 2 2015 - 2018

Run 3 2022 - 2025

Run 4 2029 - 2032

Run 5

Run 6

ATLAS | ATLAS phase I upgrades | ATLAS phase II upgrades

CMS | CMS Phase I upgrades | CMS phase II upgrades

LHCb | LHCb upgrade I(a) | LHCb upgrade Ib | LHCb upgrade II

ALICE 1 | ALICE 2 upgrade | ALICE 2.1 upgrade | ALICE 3 upgrade

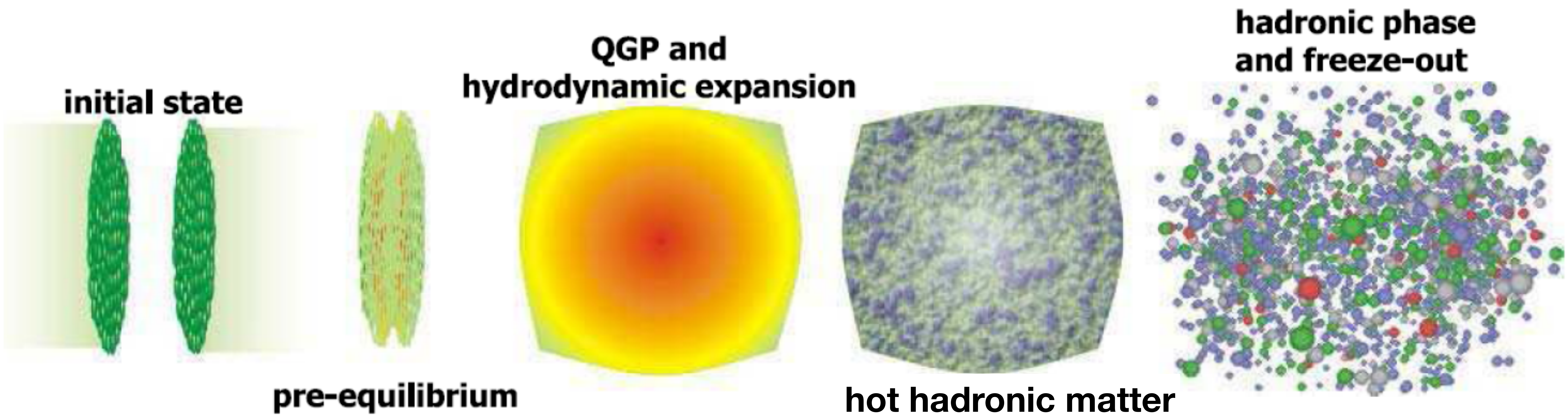
More during the talk

Intermediate upgrade

Major upgrade

Focus 1: electromagnetic radiation

The little big bang

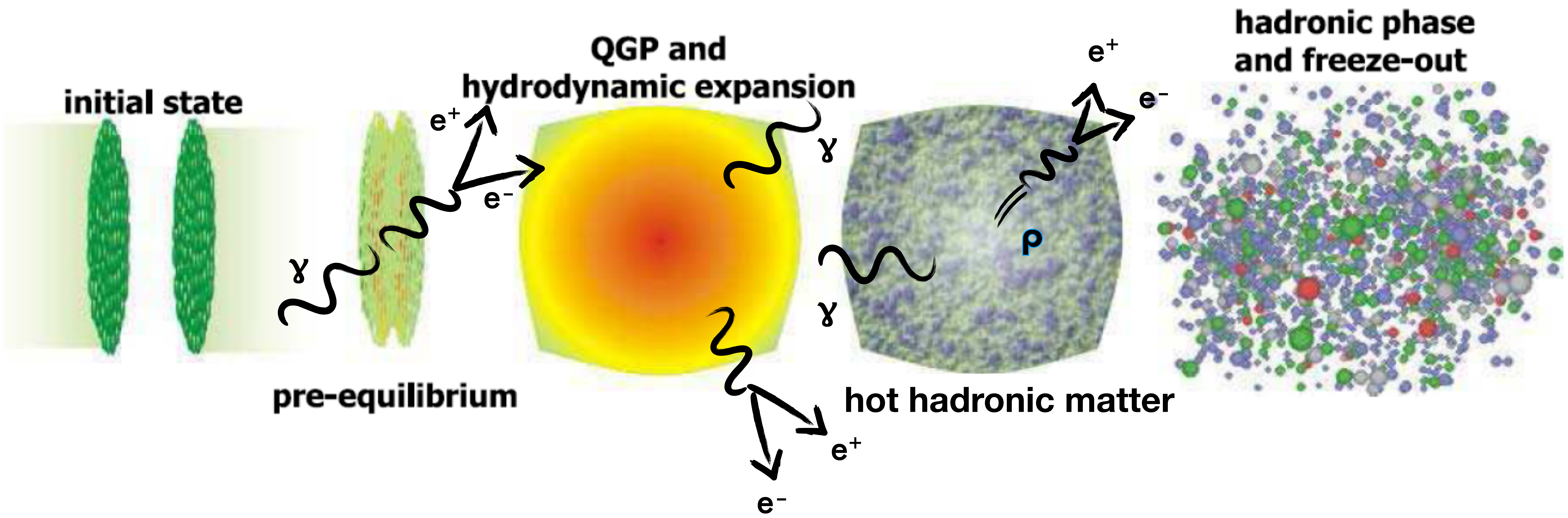


Heavy-ion collisions at the LHC:

- Little Big Bang in the laboratory: high T and μ_{B} = 0 regime accessible by lattice QCD
- Highest-temperature, longest-lived experimentally accessible QGP

Smaller colliding systems: vacuum baseline (pp) and system-size dependence

Why electromagnetic probes



Real and virtual ($\gamma^* \to l^+l^-$ dileptons) photons produced:

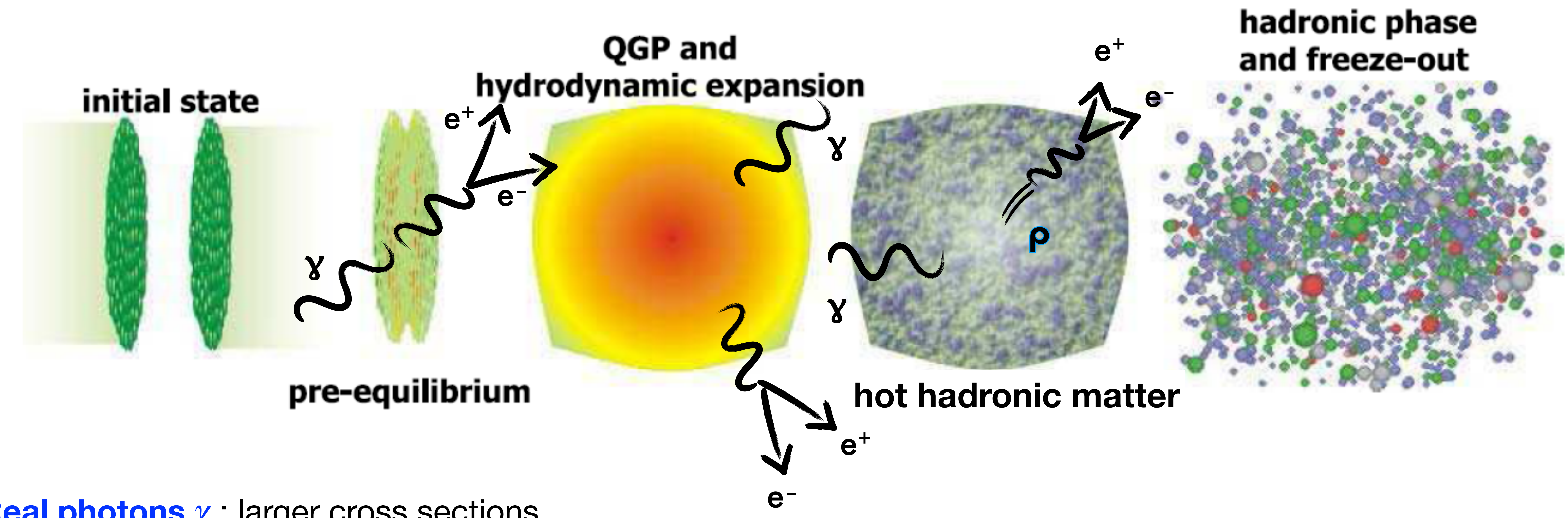
- At all stages of the heavy-ion collision
- With negligible final-state interactions

→ **Carry information about the medium at the time of their emission !**

→ **Probe the whole space-time evolution of the system**

Apologize:
Write $e^\pm$ meaning $e^\pm$ & $\mu^\pm$

Why dileptons



Real photons γ : larger cross sections

Dileptons:

- Additional invariant mass m_{ll} variable
  - Not affected by radial flow (no blueshift)
  - Additional mean to disentangle contributions in time
- Sensitivity to in medium spectral function of ρ mesons

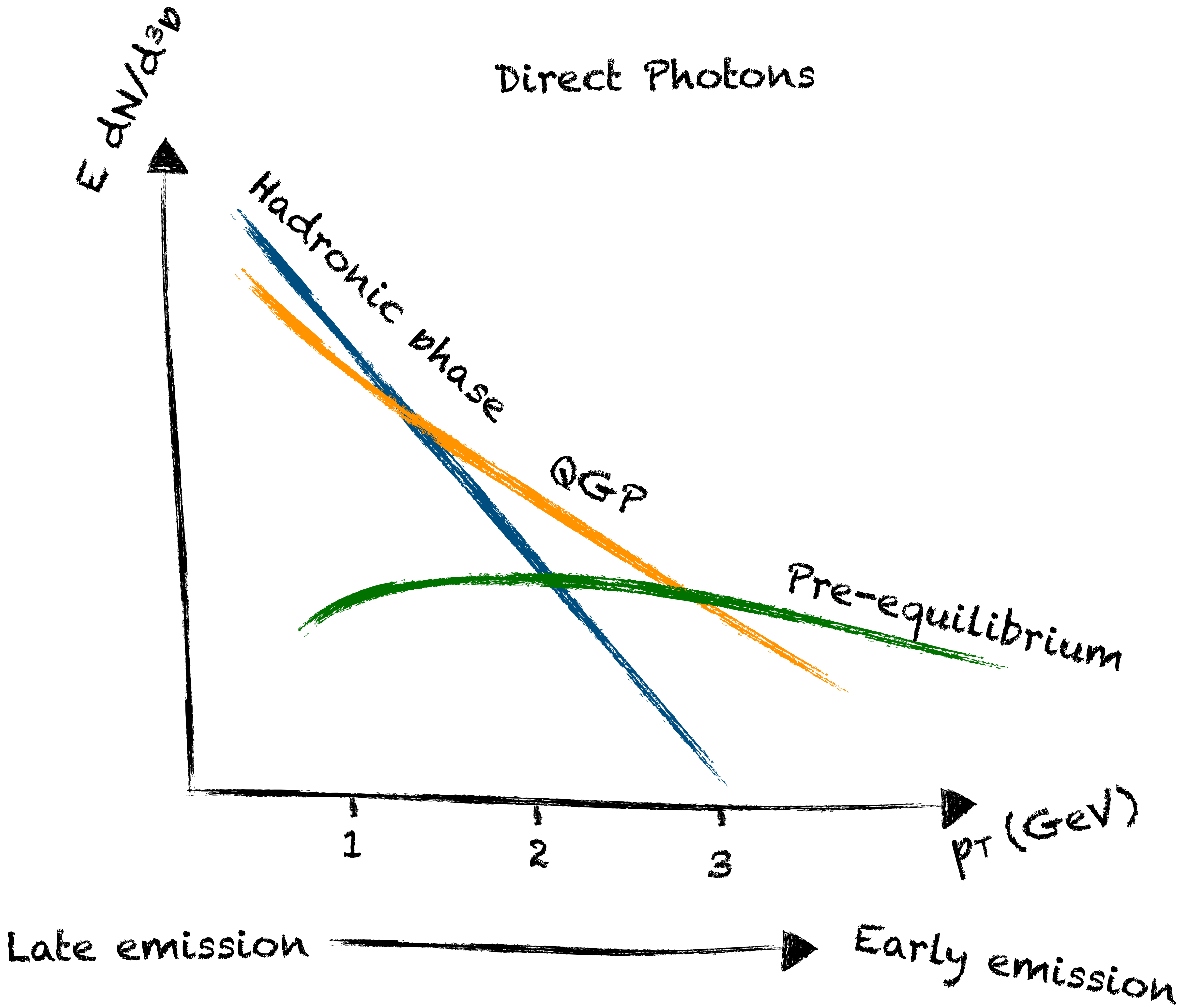
But challenging measurement !

Direct photon sources

Not from hadronic decays

- Hard scattering
  (Prompt photons + possible jet-medium interaction)
- **Pre-equilibrium**
- **Thermal from QGP**
- **Thermal from hot hadronic matter**

Sources populate different p_T ranges



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Direct photon sources

THE source in pp collisions

- Hard scattering
  (Prompt photons + possible jet-medium interaction)
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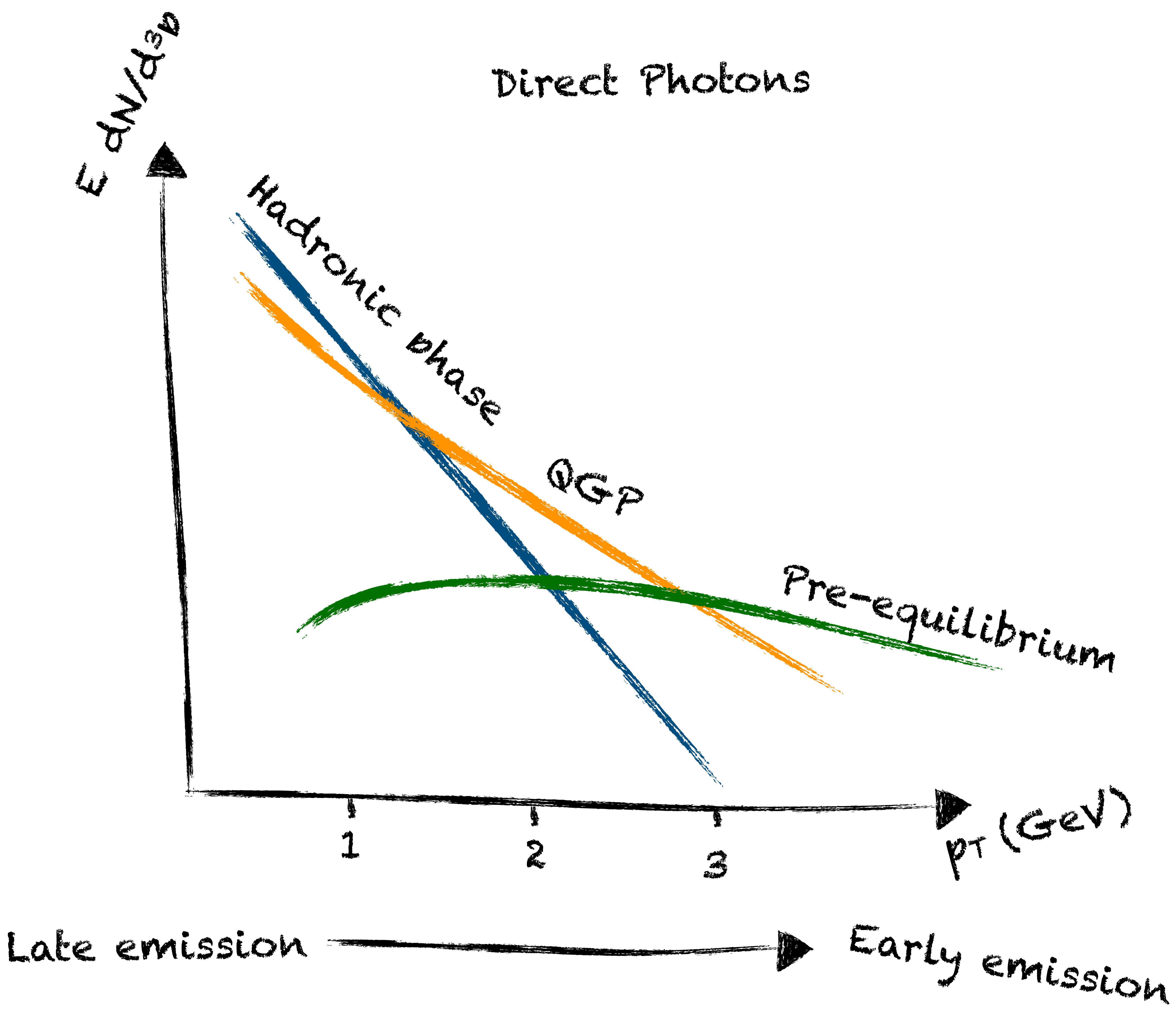

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Direct photon sources

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- **Thermal from QGP**
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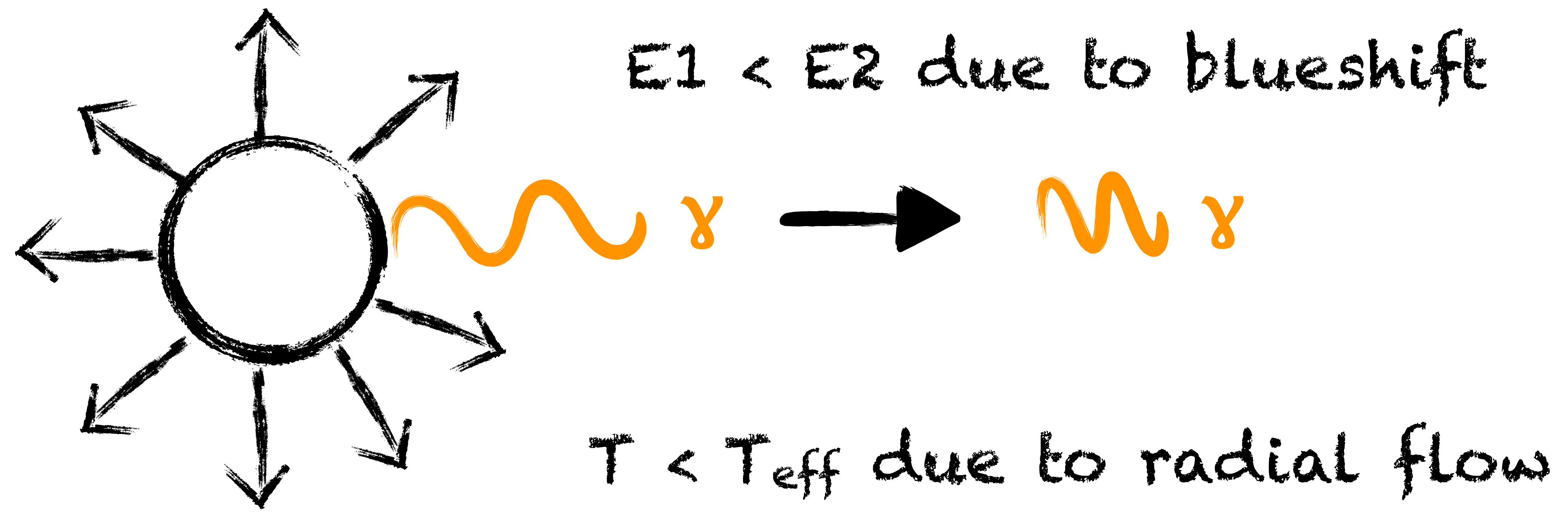
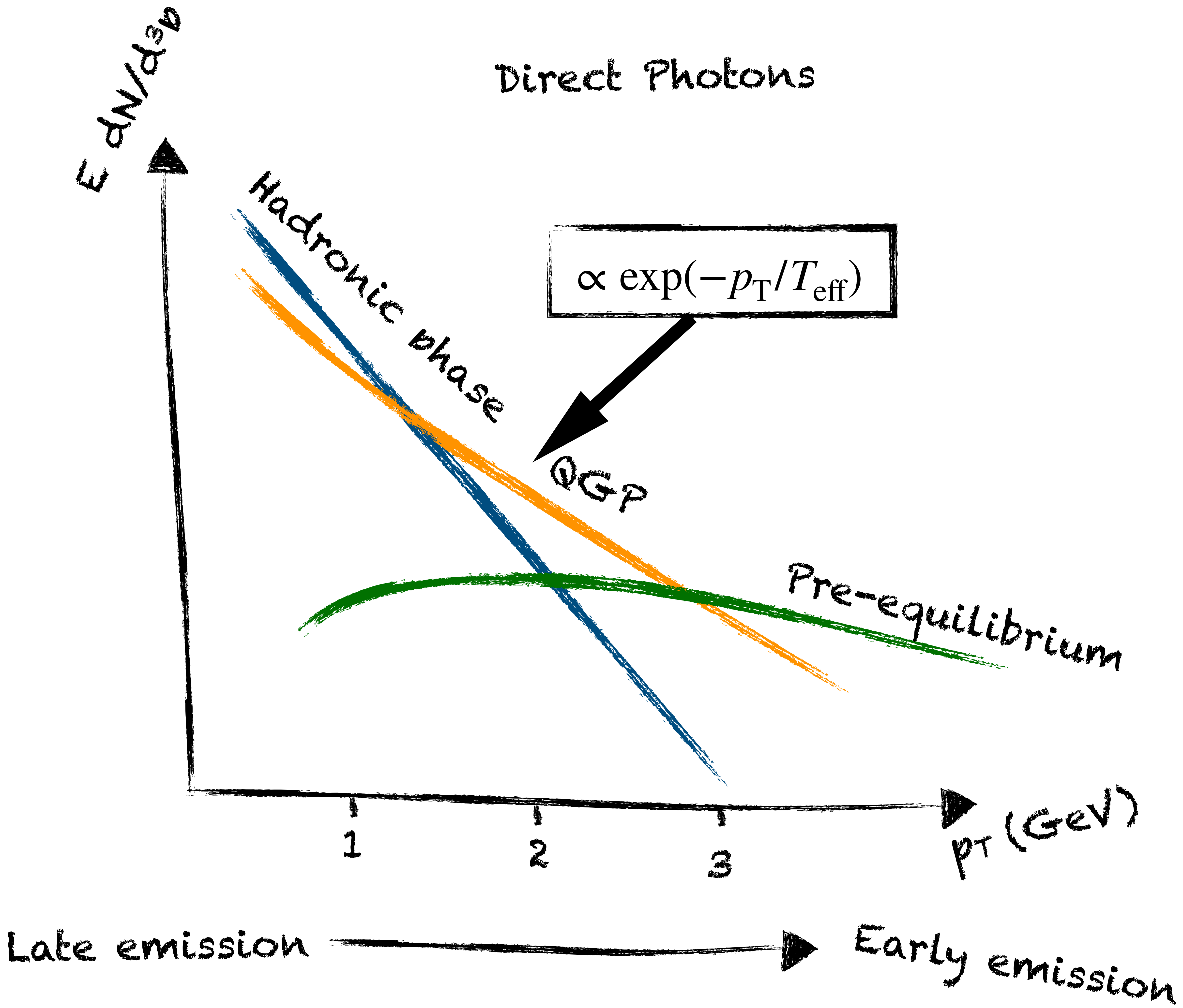
Sources populate different p_T ranges

Thermal sources: inverse slope $\propto T_{eff}$

Blueshifted and averaged → Use models to interpret it





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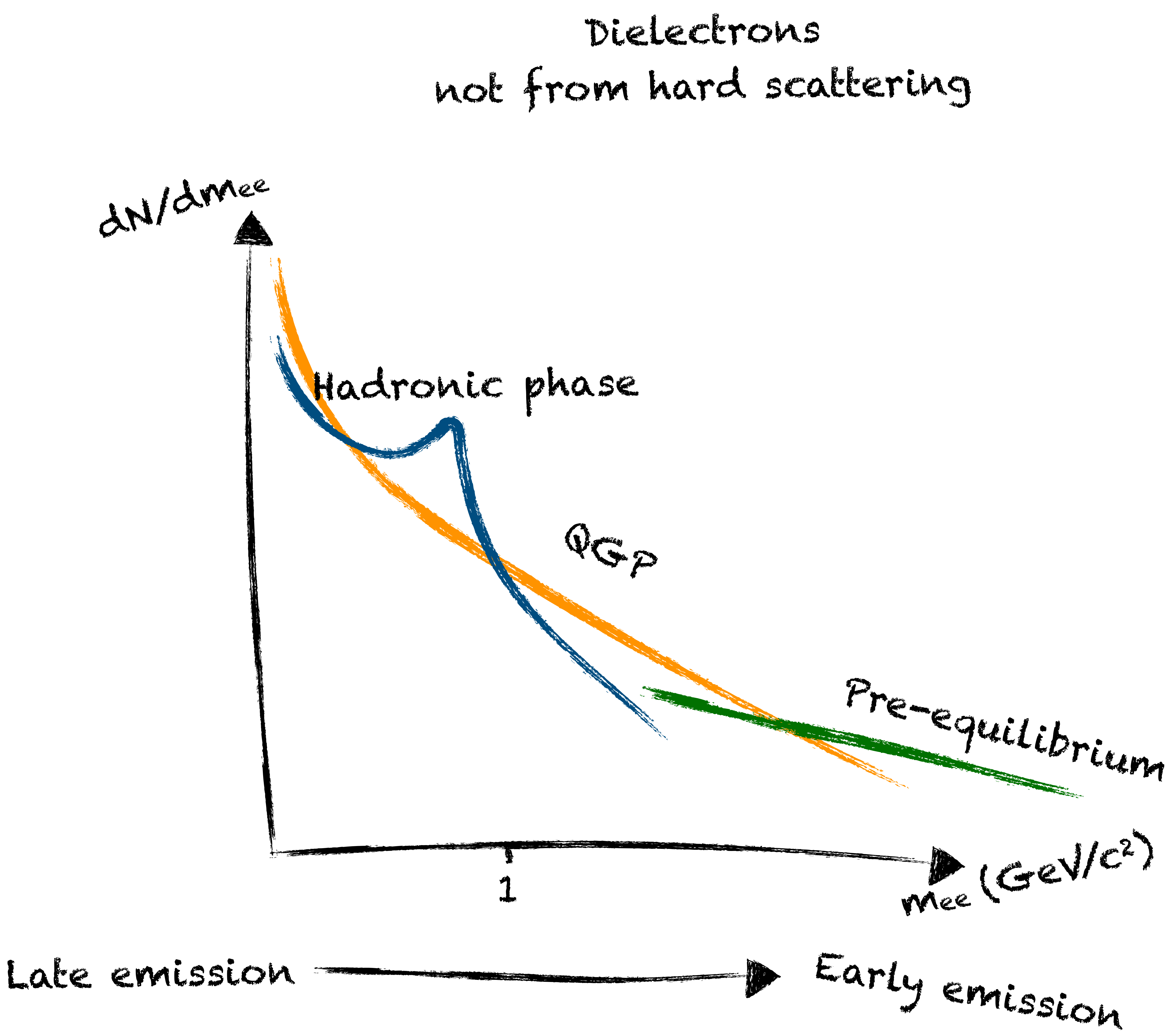
Dilepton sources

- Hard scattering
  Drell-Yan small for low $m_{\mathrm{ee}}(\leq 3$ GeV/*c*) at the LHC
- **Pre-equilibrium**
- **Thermal from QGP**
- **Thermal from hot hadronic matter**

Sources populate different mass ranges
Mass not blueshifted



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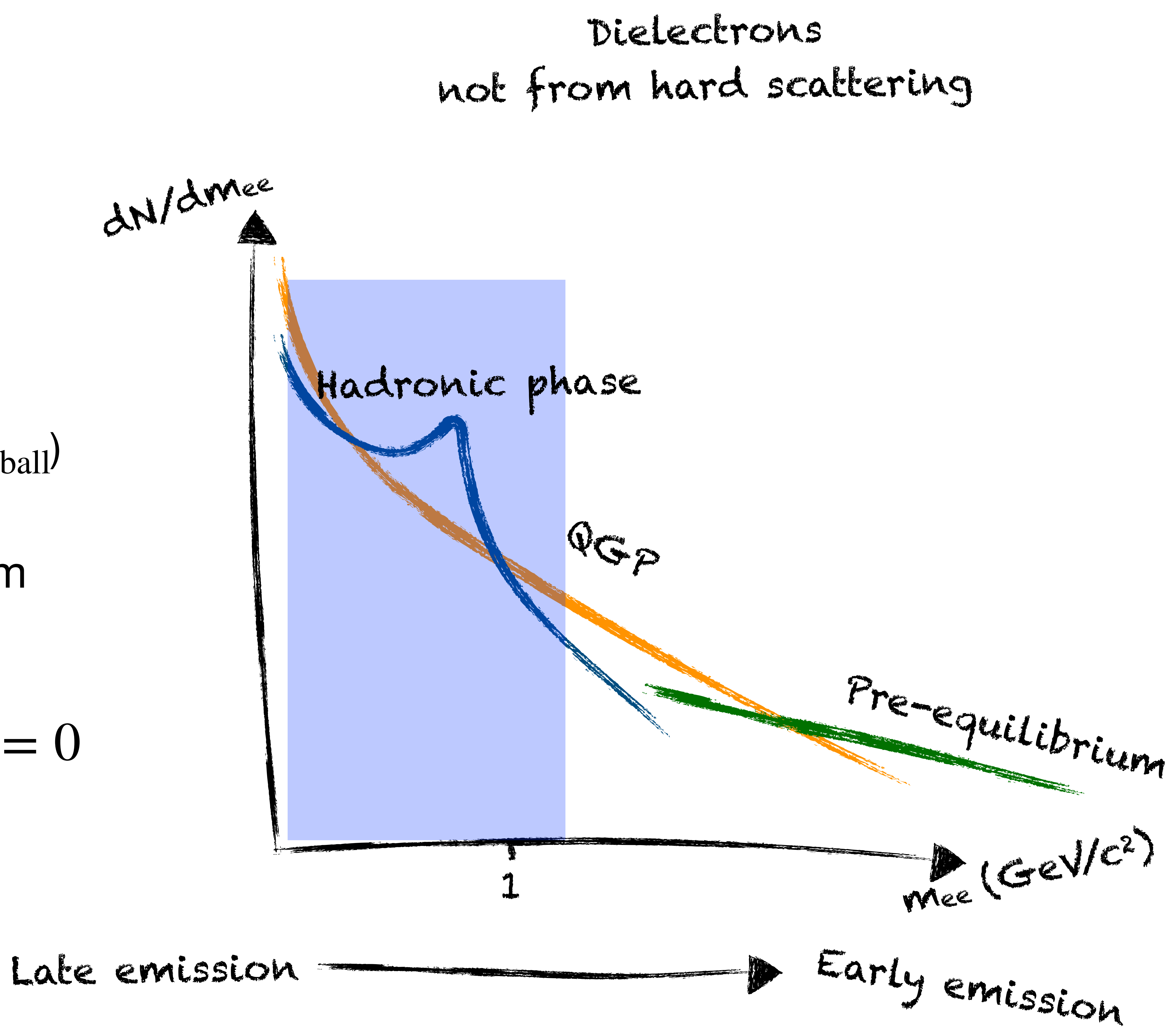
Low invariant mass (LMR)

$\rho \to \gamma^* \to e^+e^-$
produced thermally in the hot hadronic matter

- ρ sensitive to surrounding medium ($\tau_\rho = 1.3\,\mathrm{fm} < \tau_{\mathrm{fireball}}$)
- Modifications of ρ spectral function in the hot medium
  Related to the chiral symmetry restoration at high T

→ Study chiral symmetry restoration mechanisms at $\mu_B = 0$



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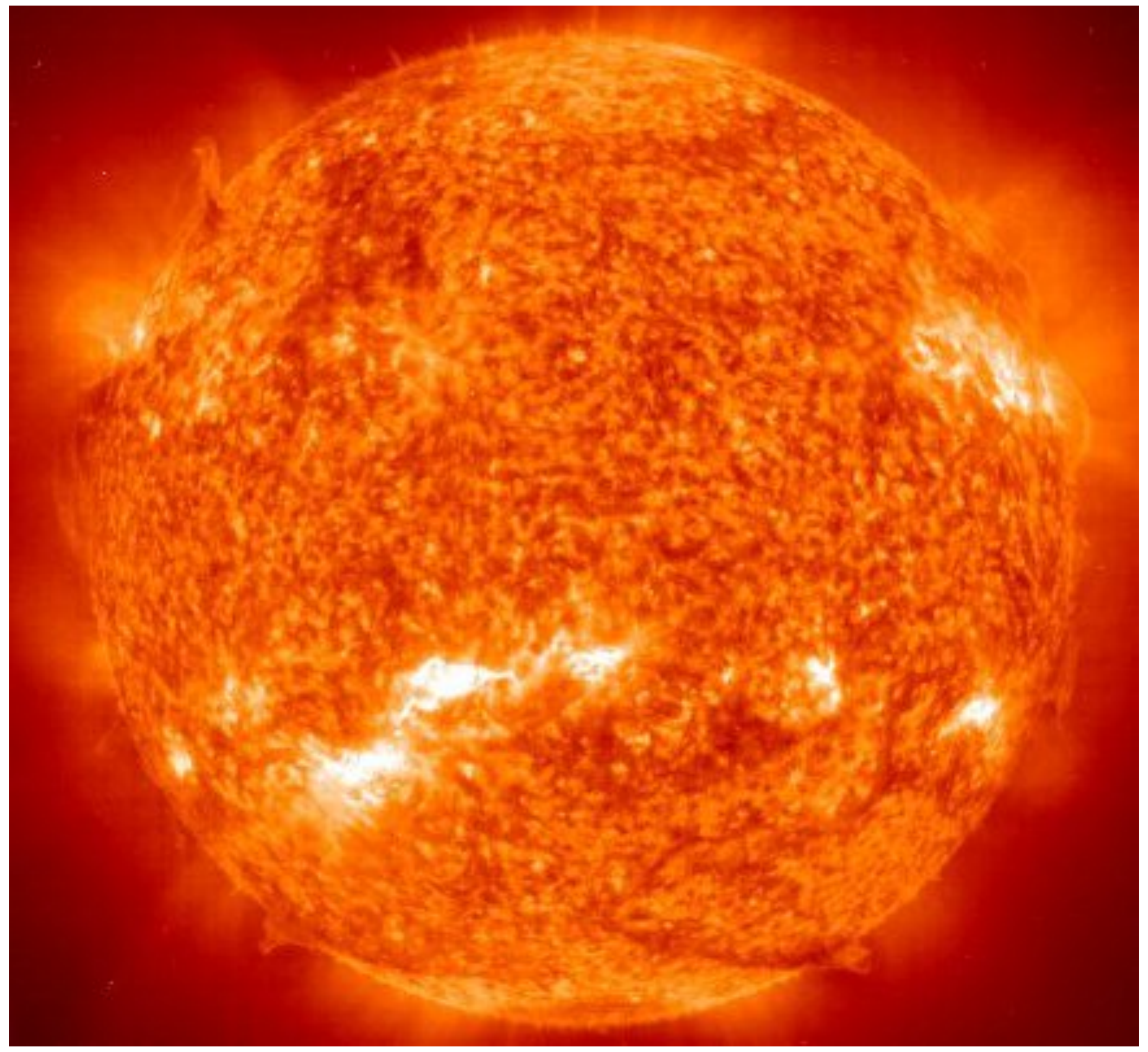
See lecture by Ralf Rapp

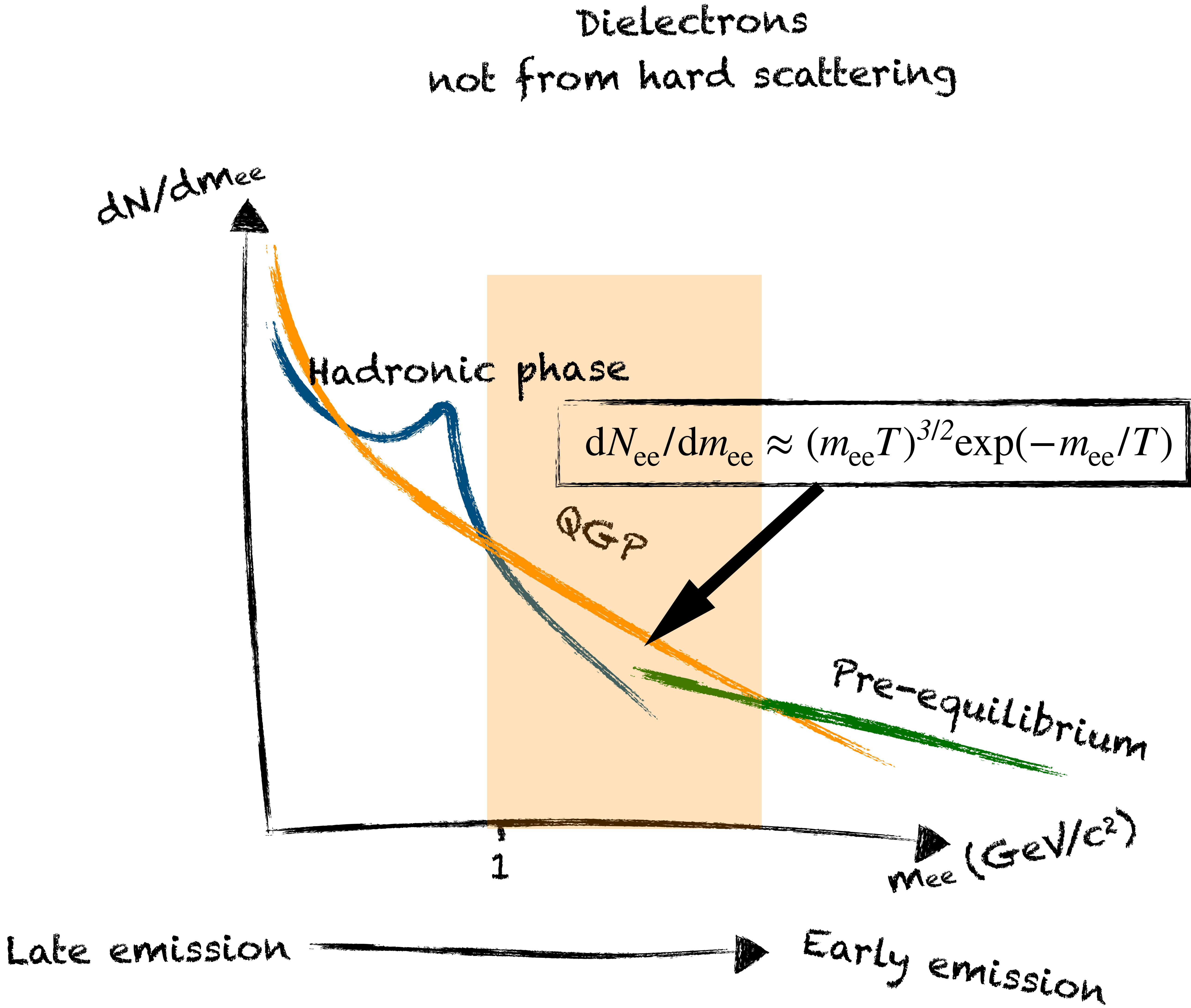
Intermediate invariant mass (IMR)

Black-body radiation from QGP
integrated over space-time



Static source $\approx e^{-E/T}$

→ Access to early average QGP temperature
No blueshift

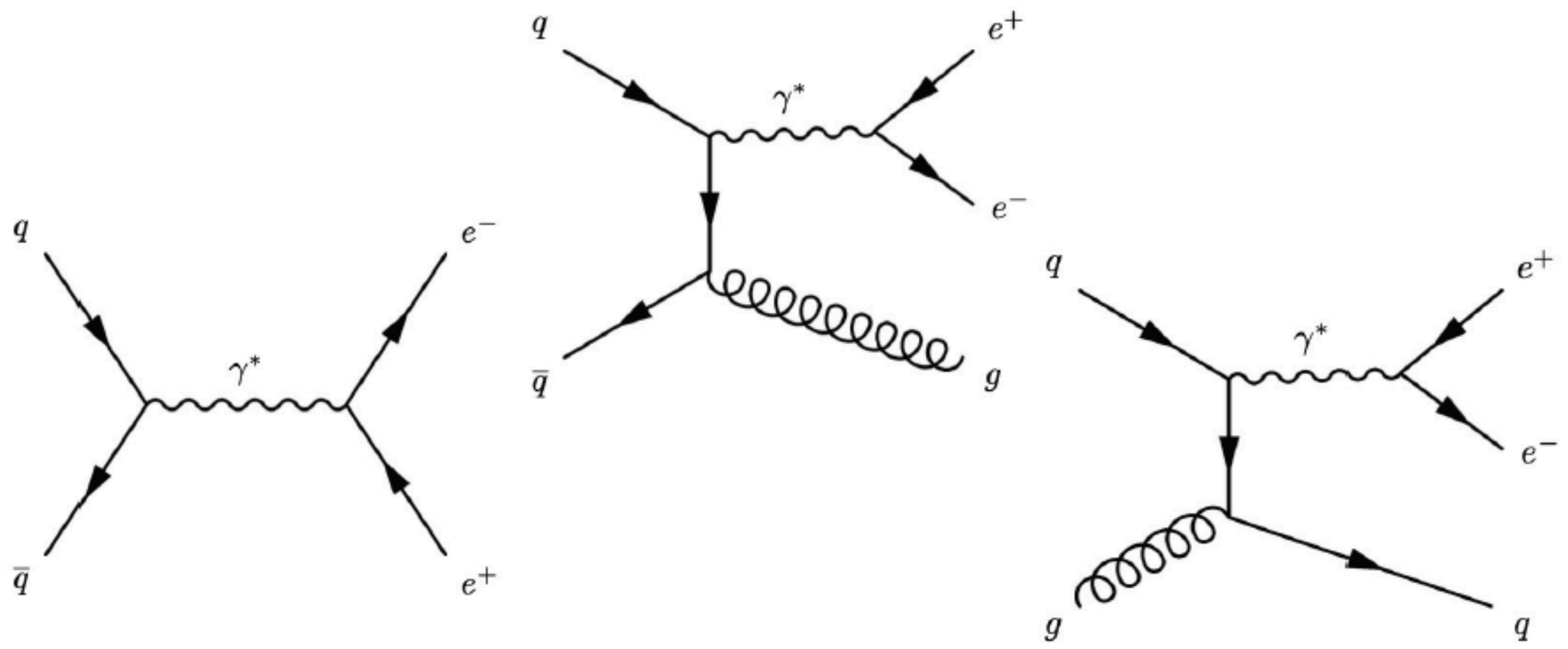


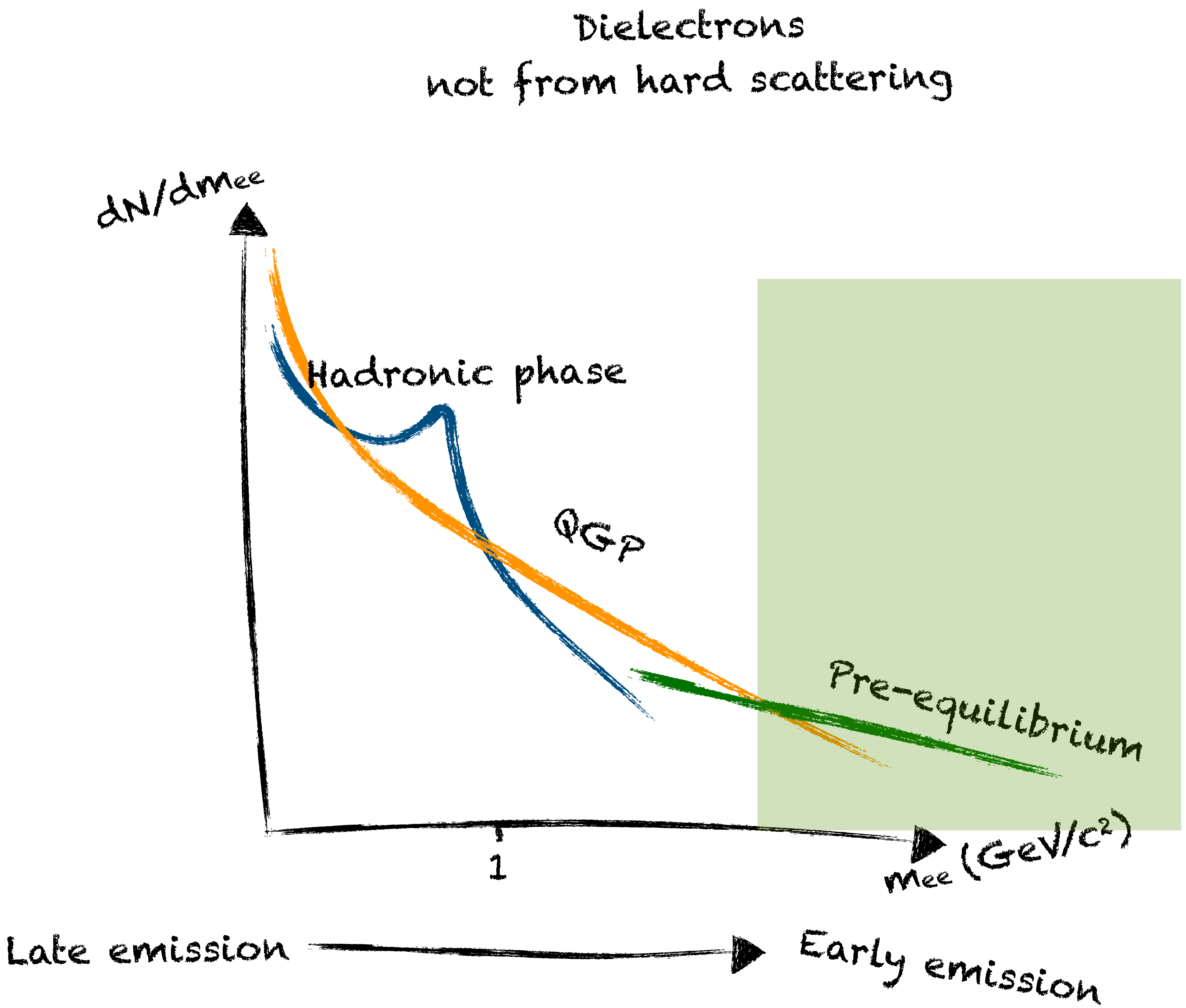
Maurice Coquet *et al*, Phys. Lett. B 821 (2021)
Maurice Coquet *et al*, arXiv:2112.13876

Higher invariant mass

e^+e^- from the pre-hydro phase sensitive to:

- Initial quark momentum anisotropy
- Early quark abundance
  (Initial stage gluon dominated)
- Equilibration time (related to η/s)





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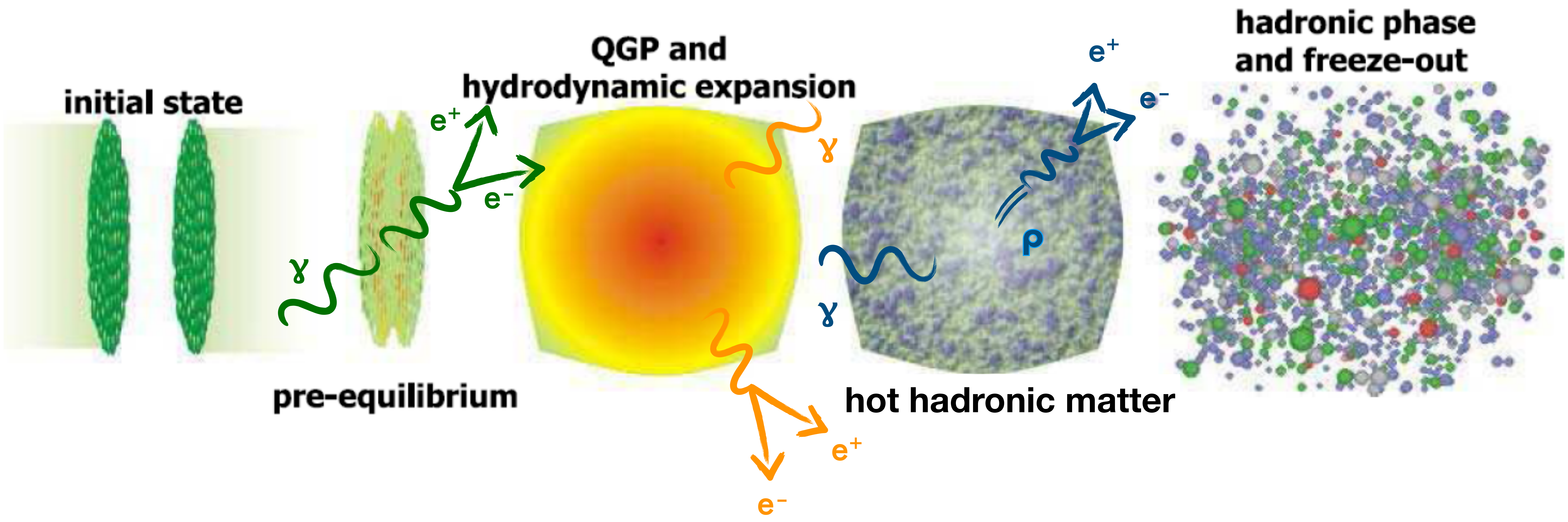
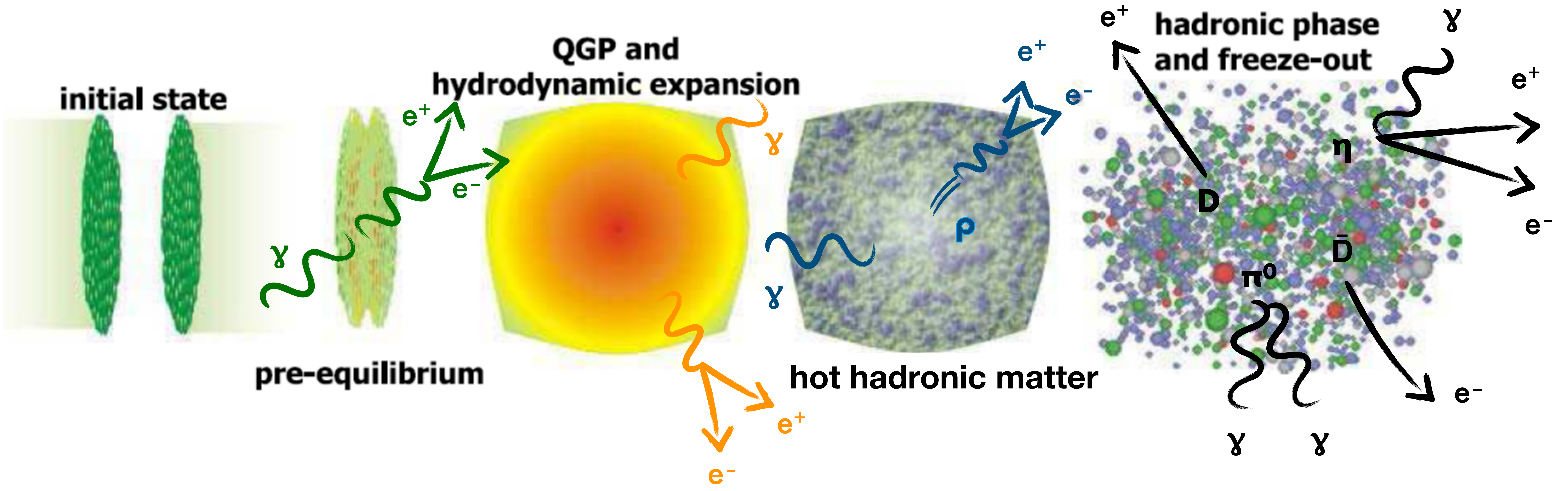
The sources


initial state
pre-equilibrium
QGP and
hydrodynamic expansion
hot hadronic matter
hadronic phase
and freeze-out
γ
e+
e−
ρ

The sources and background

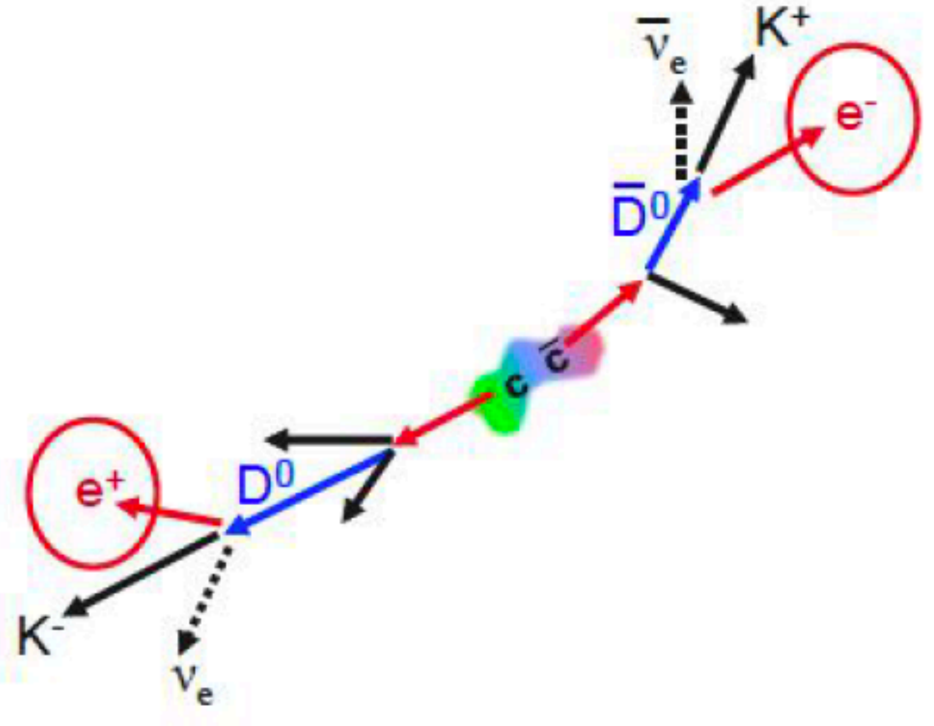


Late stage hadron decays

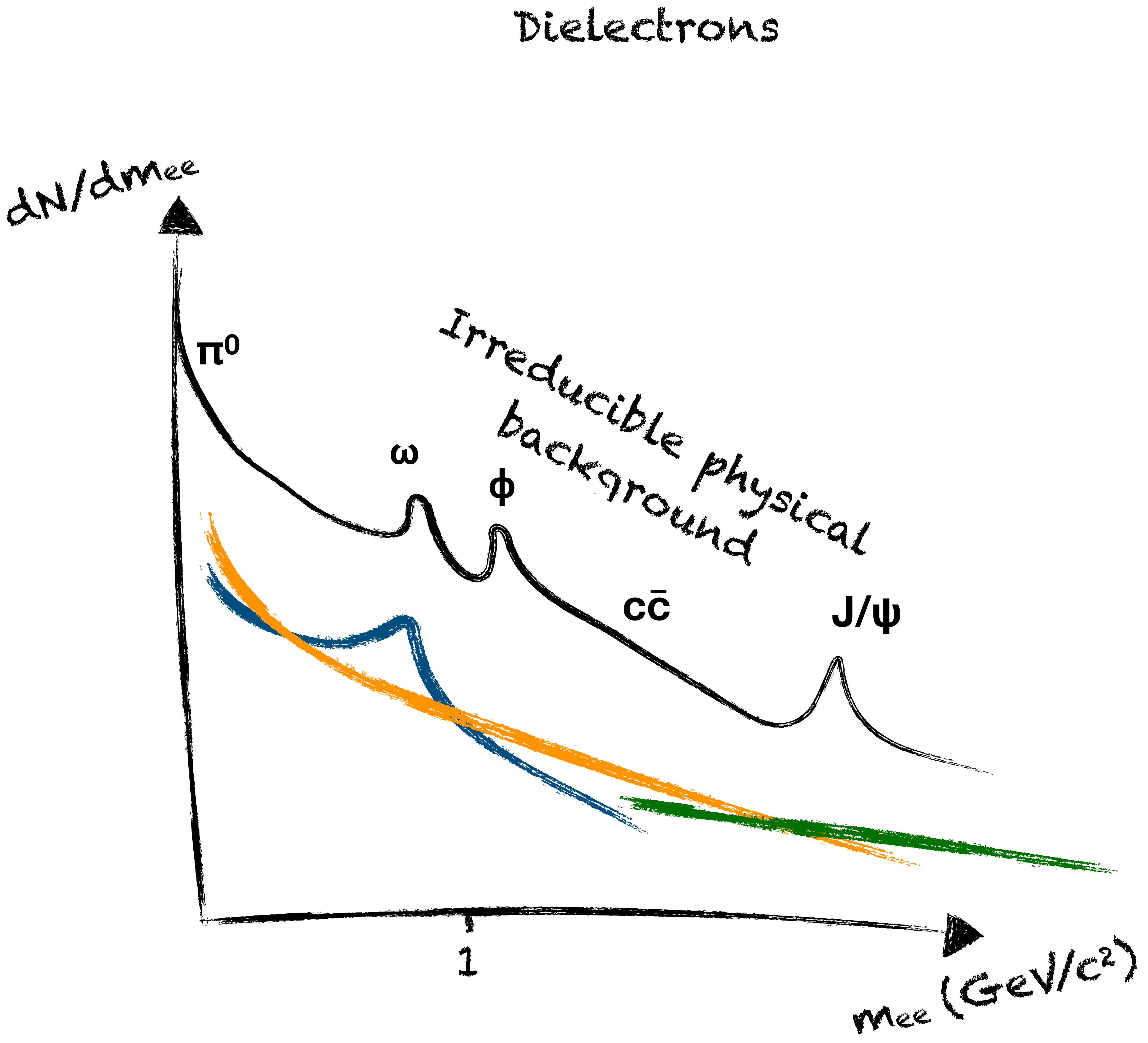
The backgrounds

- **Combinatorial background**
  - Do not know the origin of $e^{\pm}$
    $\rightarrow$ Combine all possible e^+e^- pairs

- **Irreducible physical backgrounds**
  - Light-flavour hadron decays: $\pi^0 \rightarrow \gamma e^+e^-, \eta \rightarrow \gamma e^+e^-$..
  - Correlated heavy-flavour (HF) hadron decays:
    $c\bar{c} \rightarrow D\bar{D} \rightarrow e^+e^-XY$



Very large heavy-flavour cross sections at the LHC !



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The backgrounds

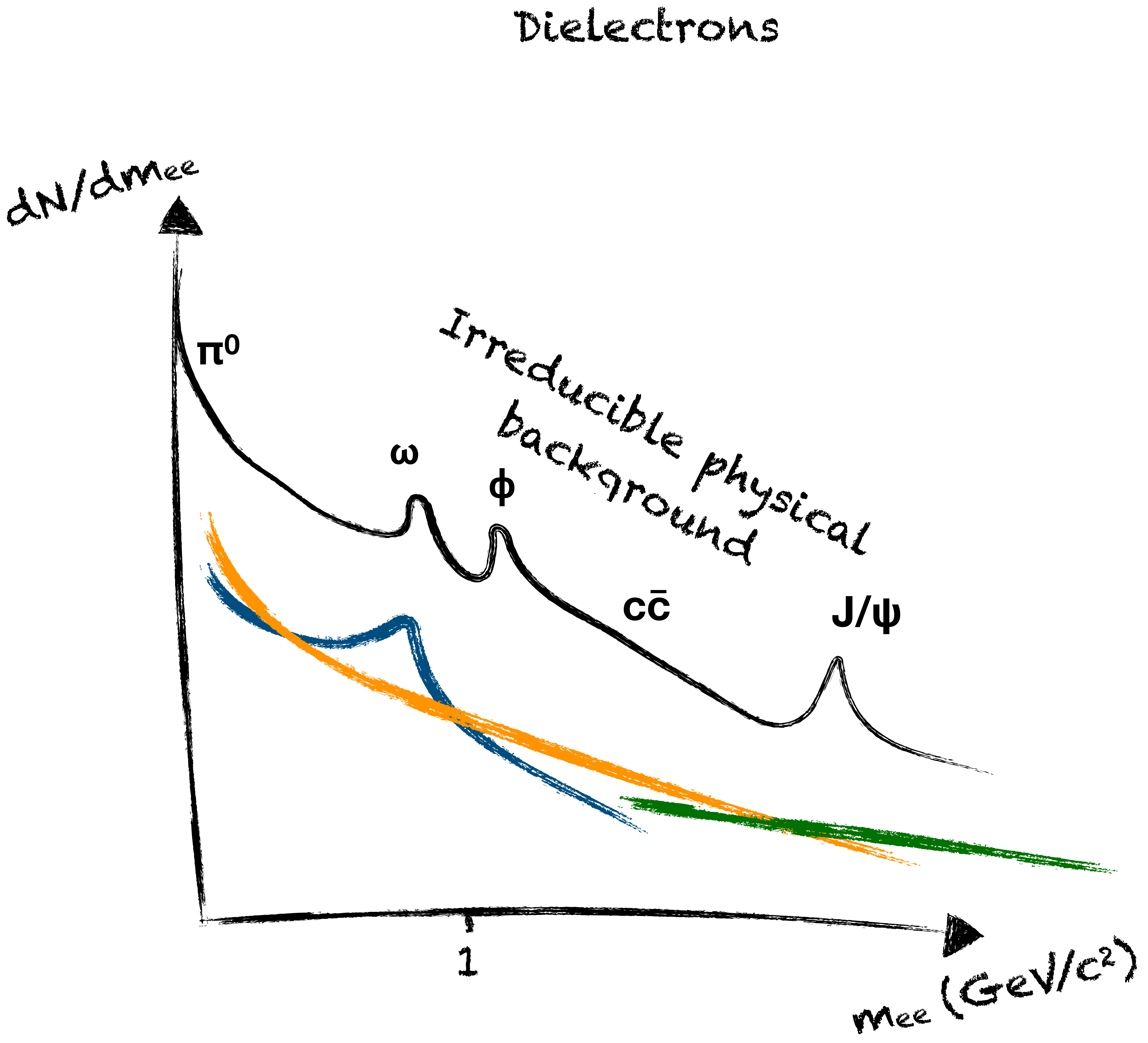
- **Combinatorial background**
  Estimated and **subtracted** with $e^{\pm}e^{\pm}$ or mixed events
  Reduced with less detector material + low p_T coverage

- **Irreducible physical backgrounds**
  - Light-flavour (LF) hadron decays
  - Correlated heavy-flavour (HF) hadron decays

  Estimated based on measurements + calculations

  → **Hadronic cocktail**

Challenging for HF due to medium effects !



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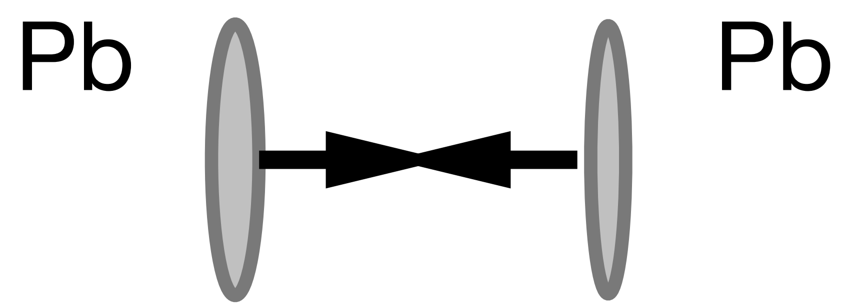
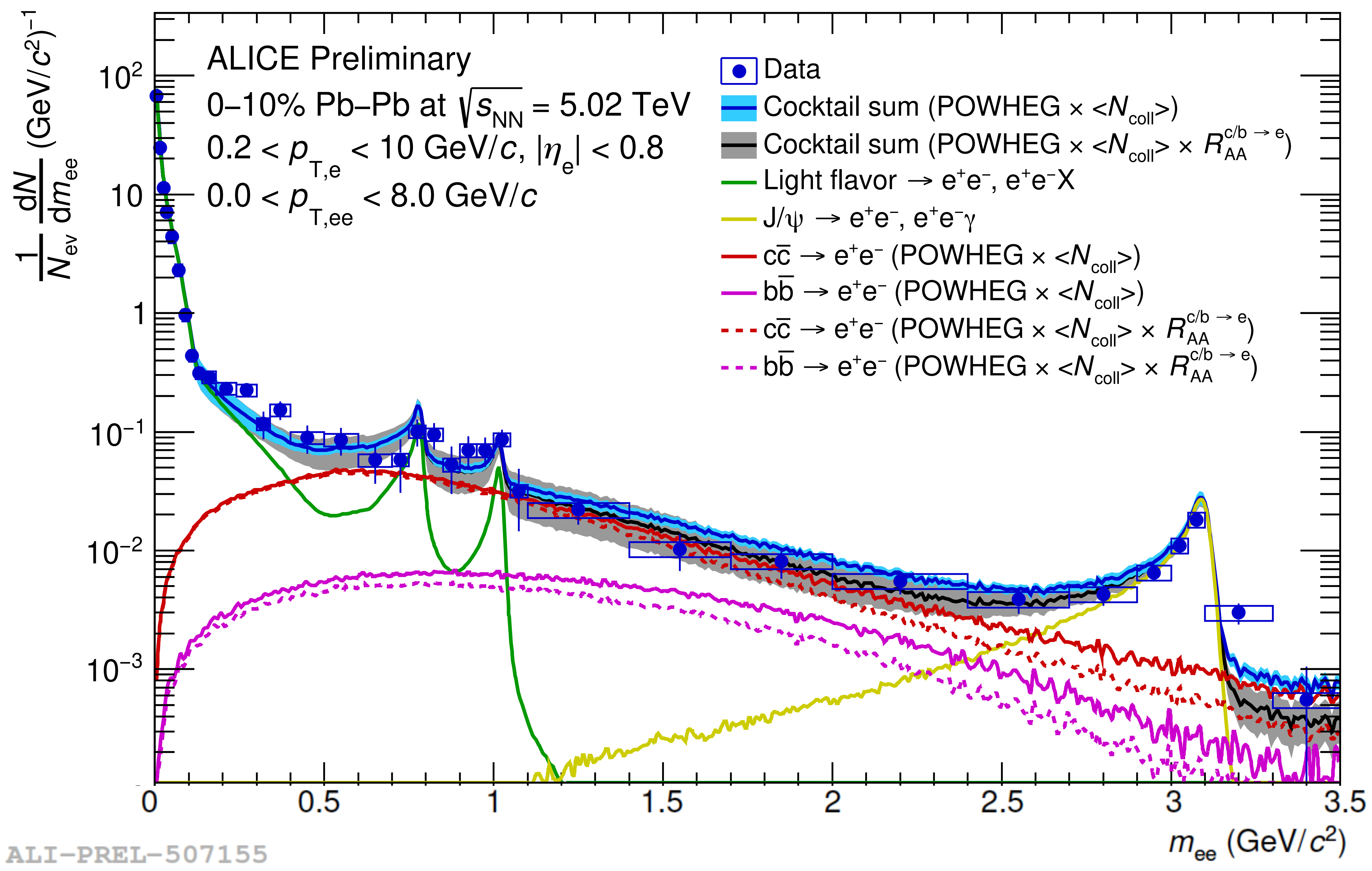
Dielectrons (Run 2)



- e^+e^- spectrum compared to hadronic cocktail

- Two different cocktails for HF:
  - **No medium effect:**
    N_{coll} scaled from pp measurement (ALICE, PRC 102 (2020) 055204)
  - **Some medium effects (model dependent):**
    Additional R_{AA} of $c/b \rightarrow e$ (ALICE, PLB 804 (2020) 135377)

0-10% Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



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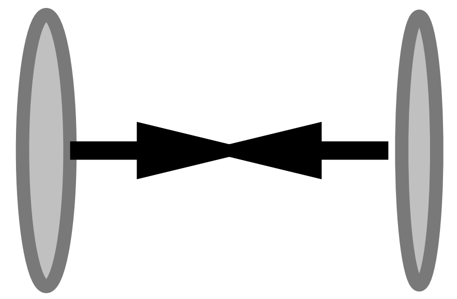
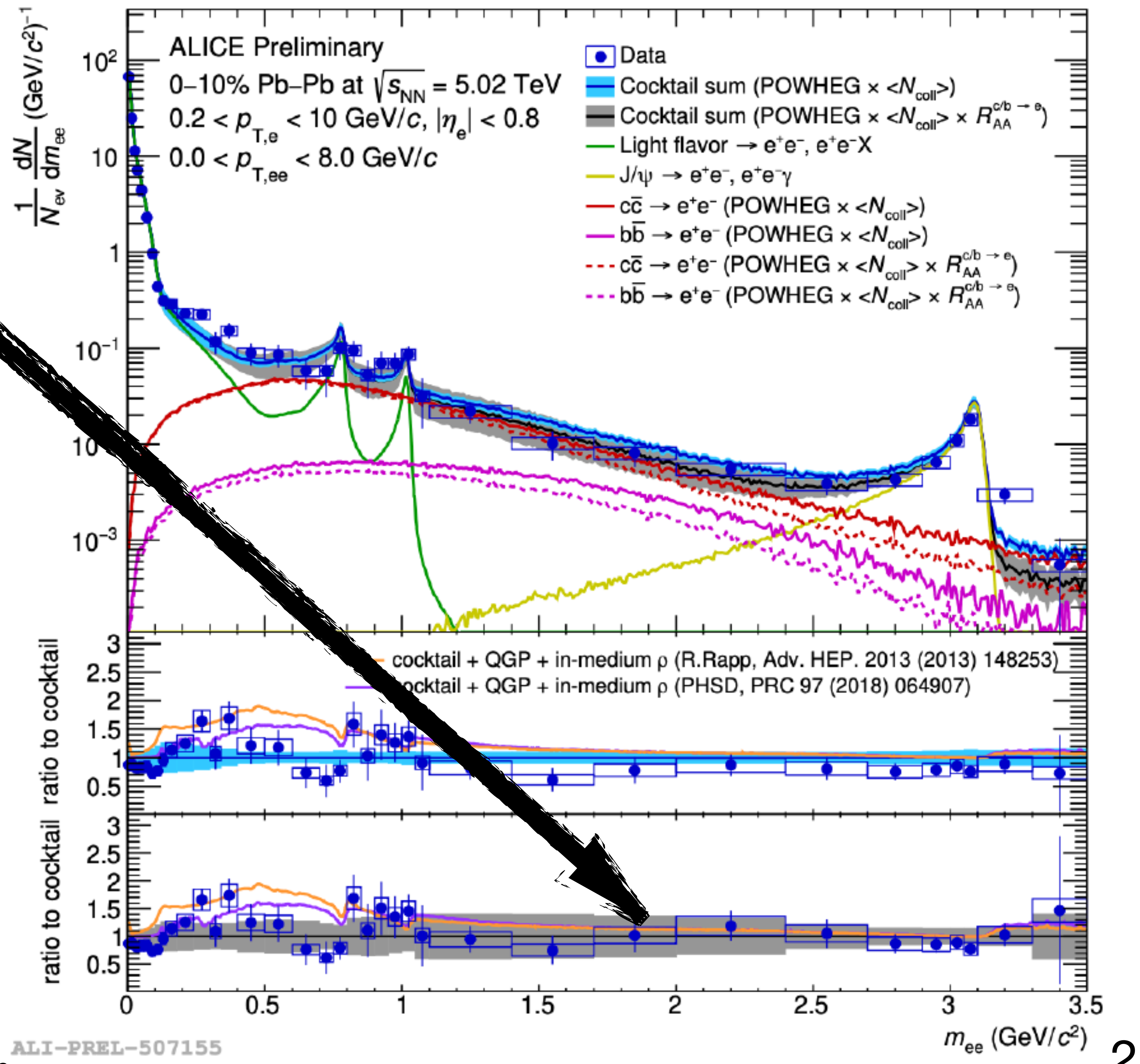


- Better agreement including some HF medium effects but huge cocktail uncertainties

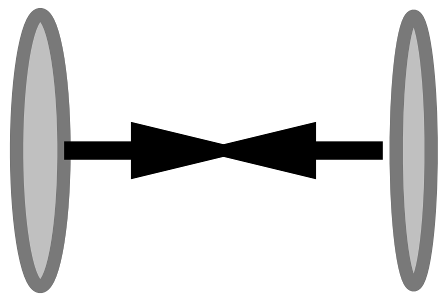
→ Need topological separation (model independent) of sources (HF and thermal)

- At $m_{ee} < 0.5$ GeV/c^2 hint for an excess
  Consistent with thermal radiation from hot hadronic matter
  - R. Rapp: fireball + hadronic many body system
  - PHSD: transport model

0-10% Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

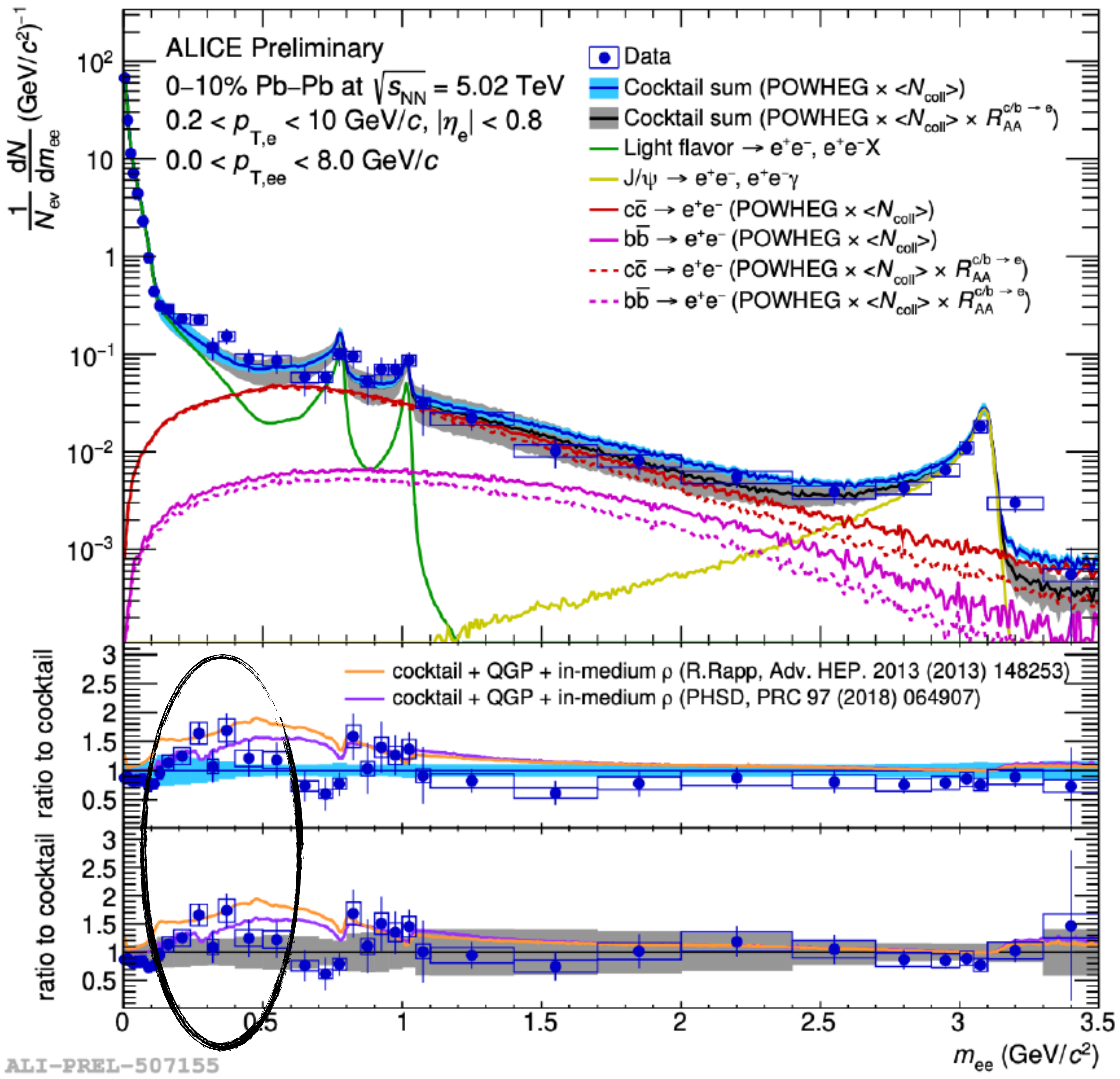


Dielectrons (Run 2)

Pb  Pb

ALICE

0-10% Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



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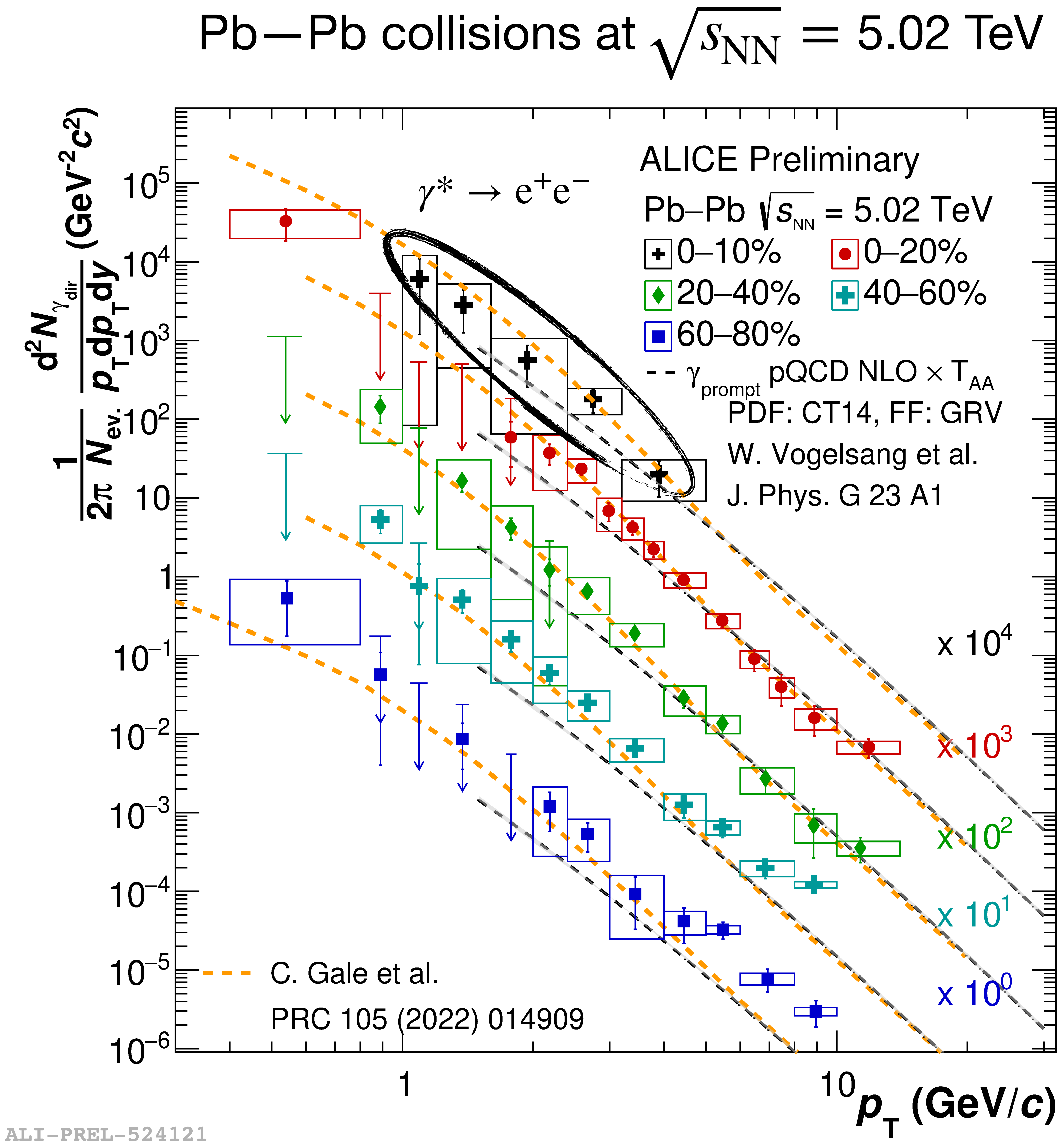
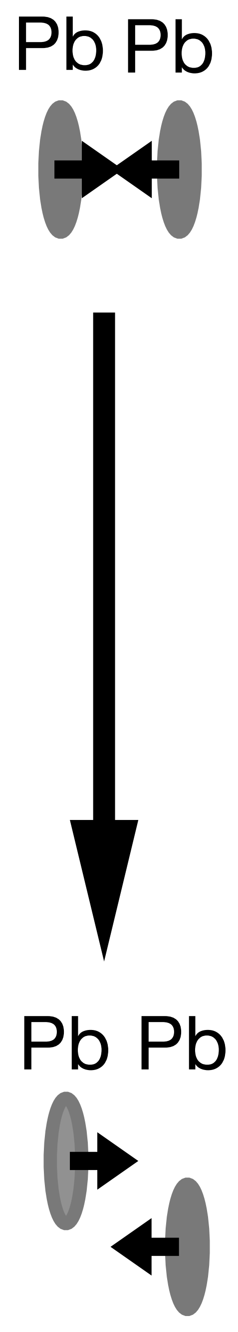
Direct real photons γ_{dir} (Run 2)

- Assuming excess (for $p_{T,ee} > 1$GeV/c) comes from γ^*_{dir}
  → Extract $\gamma_{dir}/\gamma_{inc}$ and direct real γ_{dir} yield
  → Complementary to real γ analyses

- Low p_T: hint for an excess above γ_{prompt} (hard-scattering)

- Data consistent with model including pre-equilibrium and thermal γ from QGP and hadron gas (C. Gale et al.)





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- Low p_T: hint for an excess above γ_{prompt} (hard-scattering)
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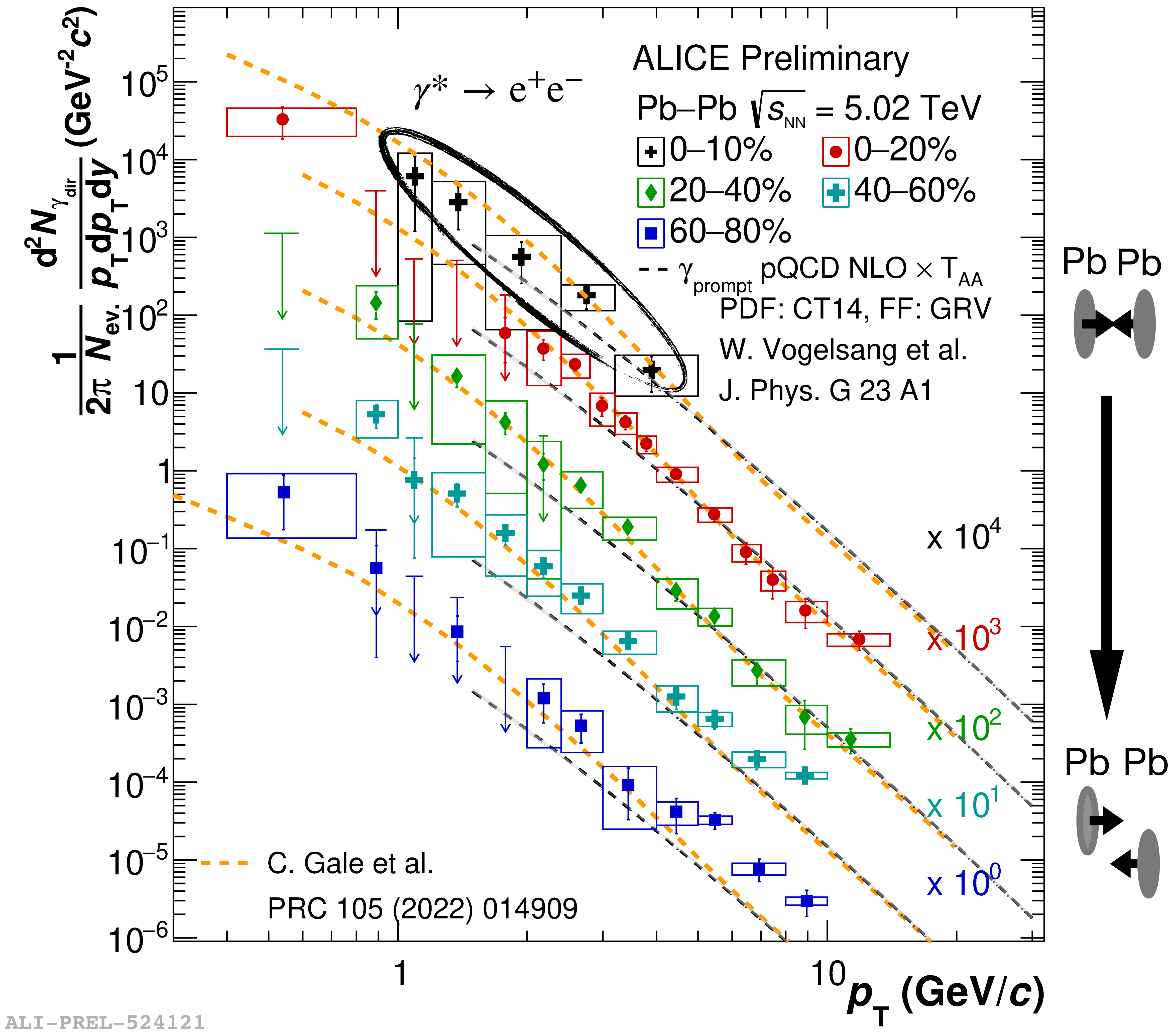
Results (yield, v_2) from real photon analyses also in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE, Phys. Lett. B 754 (2016) 235; ALICE, Phys. Lett. B 789 (2019) 308

Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



NA60, Eur. Phys. J. C59 (2009)

Topological separation of l^+l^- sources

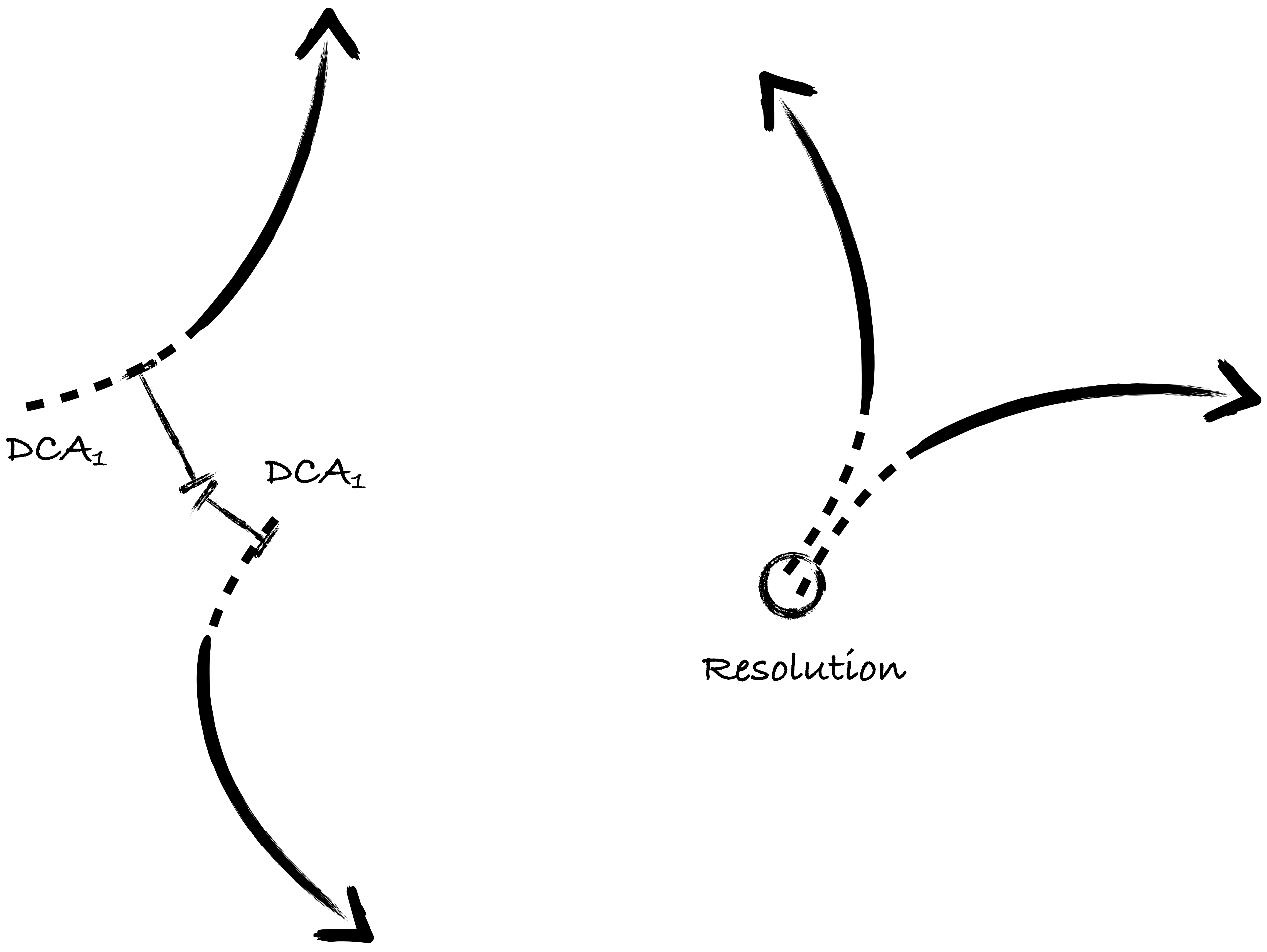
Decay length of heavy-flavour hadrons
$c\tau \approx 150\,(450)\,\mu$m for charm (beauty)

→ Use **Distance-of-closest approach to primary vertex**

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

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

→ *Need good/excellent detector pointing resolution*



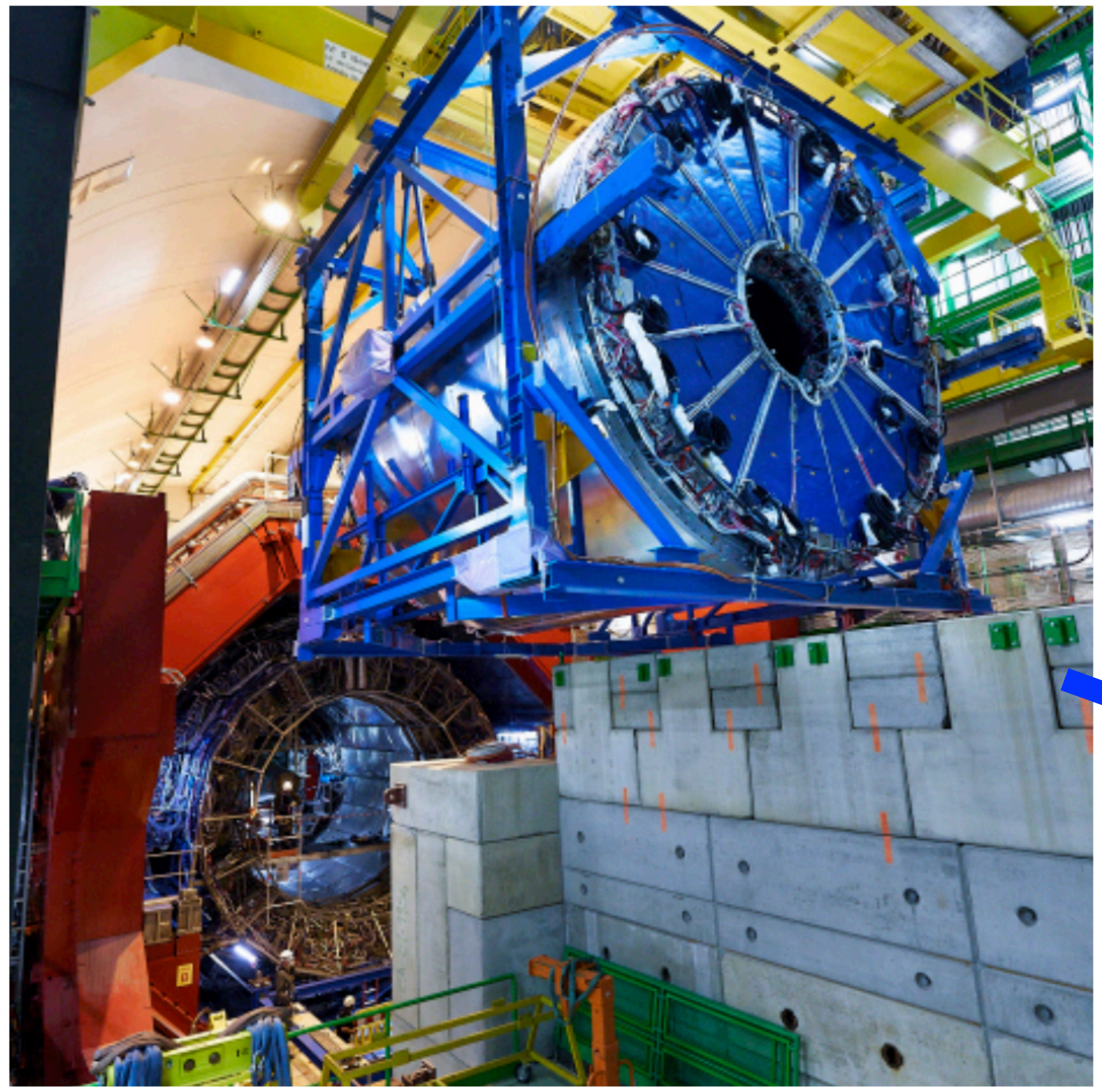
non-prompt
(Heavy-flavour)

Prompt
(Thermal)

First steps in pp and Pb—Pb collisions by ALICE (Runs 1&2)
ALICE JHEP 1809 (2018) 064

ALICE 2 upgrades (Run 3)

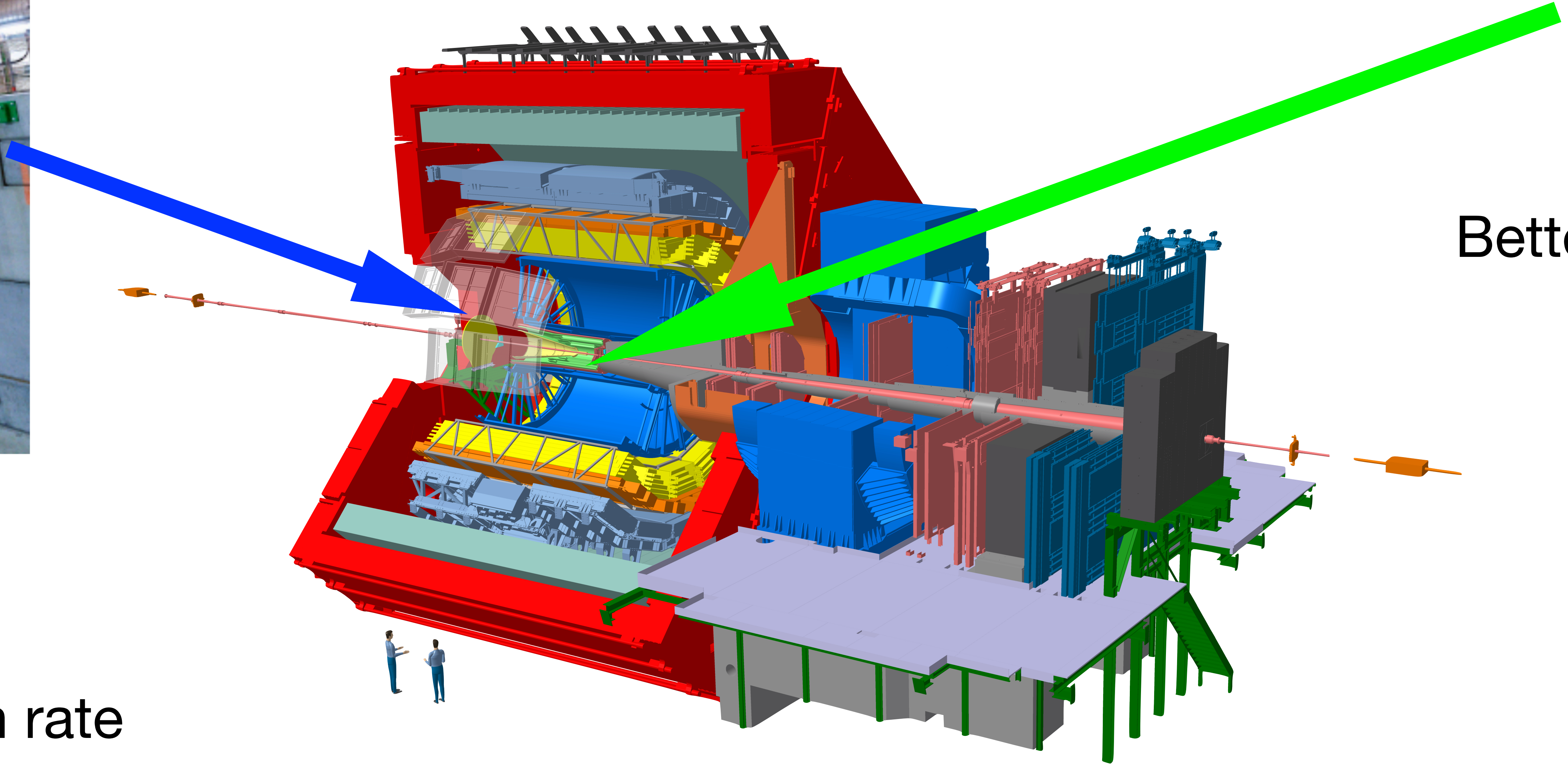
ALICE CERN-LHCC-2013-020, CERN-LHCC-2015-002



Time Projection Chamber

- GEM-based chambers
- New front-end electronics

→ Factor > 50 higher acquisition rate



New and upgraded central detectors

Continuous readout of Pb—Pb at 50 kHz

→13 nb^{-1} in Run 3 & 4

ALICE CERN-LHCC-2012-013

Inner Tracking System 2

Better pointing resolution (x3 in xy, x6 in z)

ALICE CERN-LHCC-2015-006

O2 Computing Farm

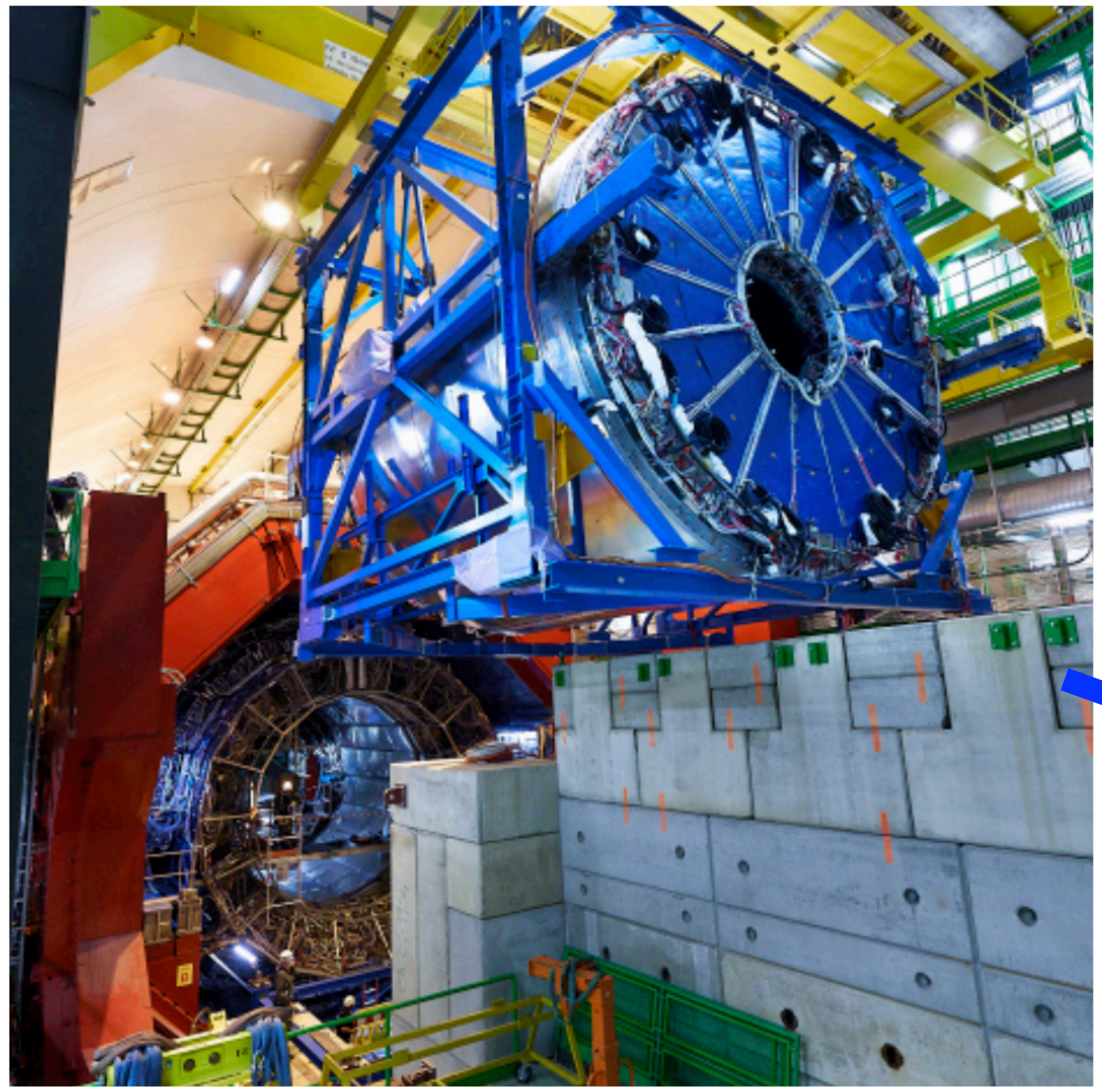
- Online Processing of all events
- Relevant for experiments at LHC, FAIR

More upgrades done/planned…

ALICE 2 upgrades (Run 4)

ALICE CERN-LHCC-2020-009

ALICE CERN-LHCC-2013-020, CERN-LHCC-2015-002



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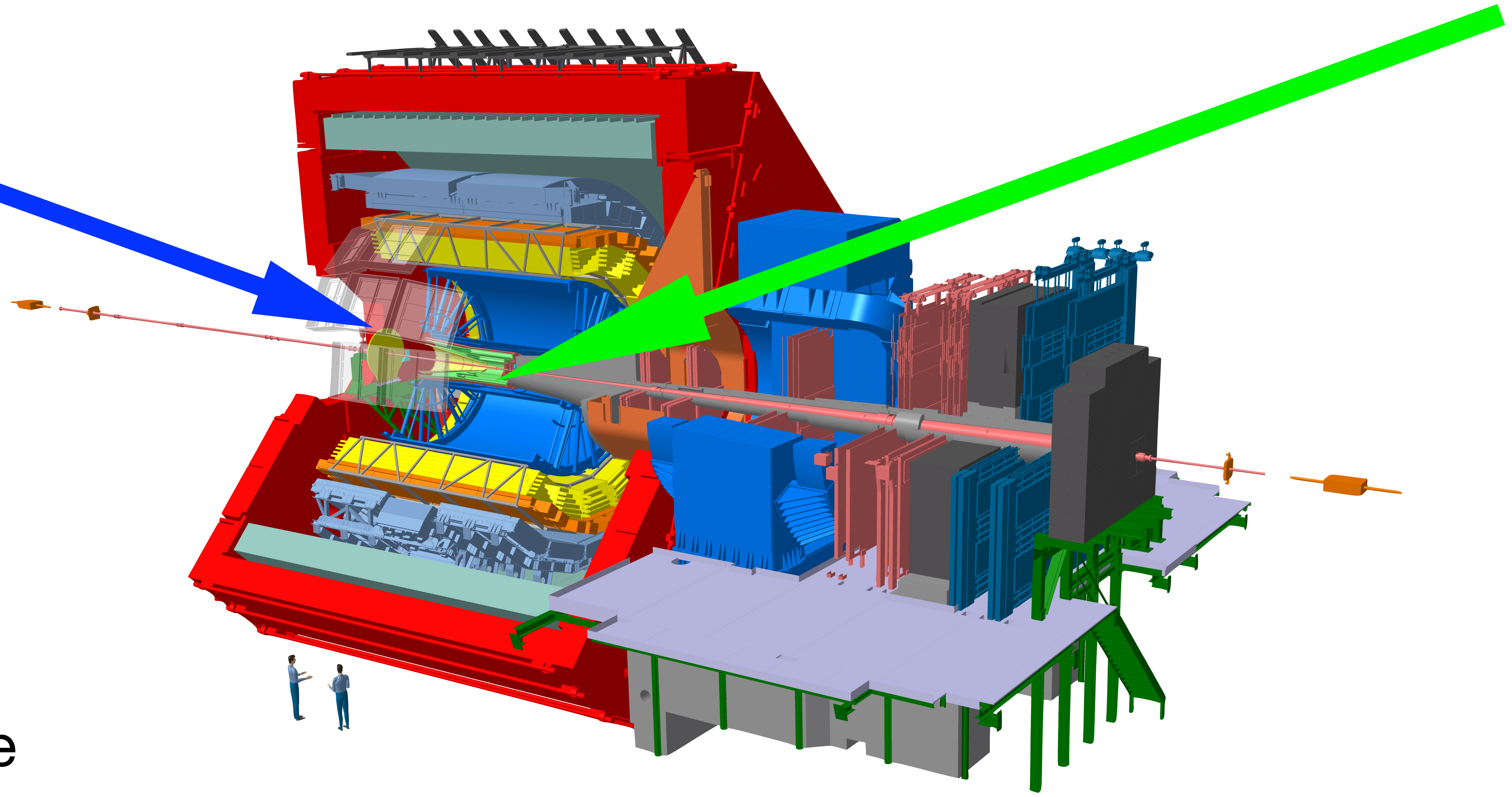

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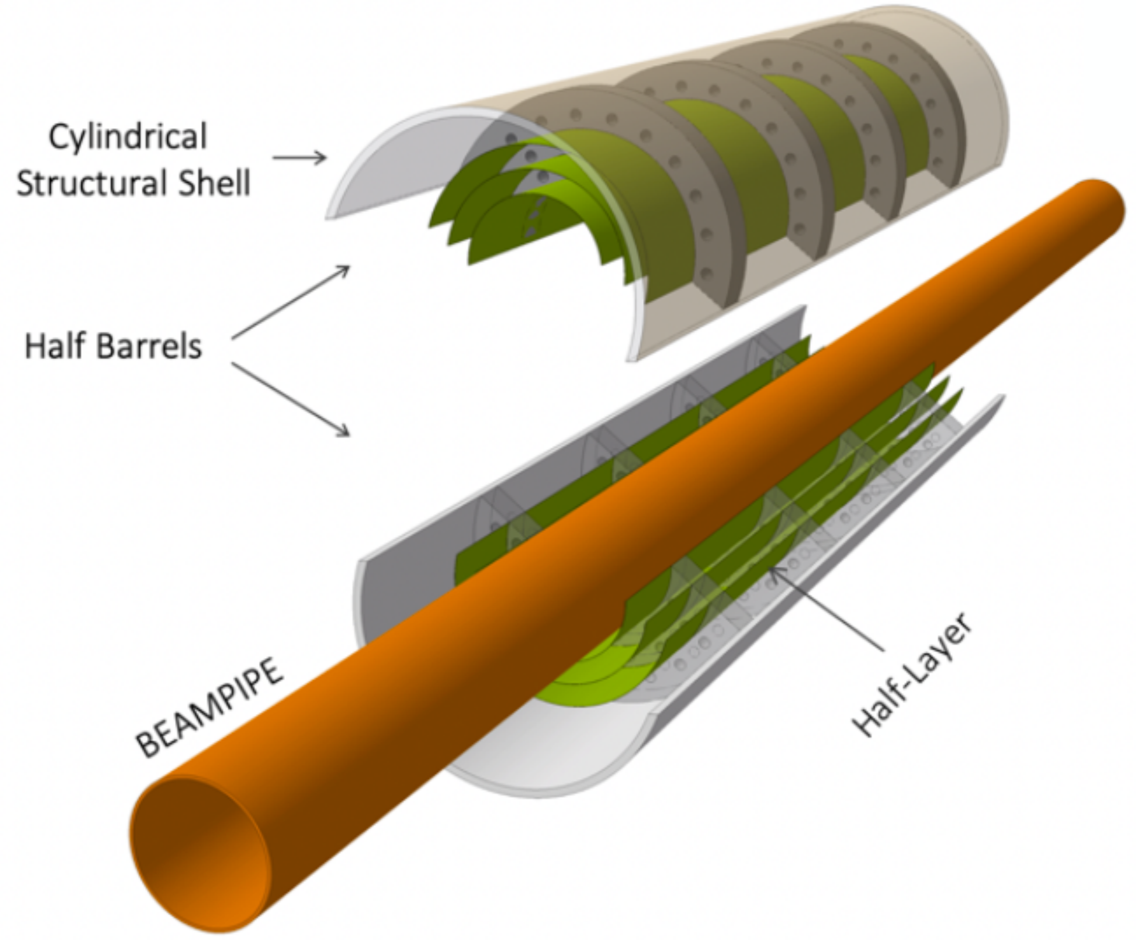


Inner Tracking System 3

→ 6x less material budget

→ 2x pointing resolution at low p_{T}

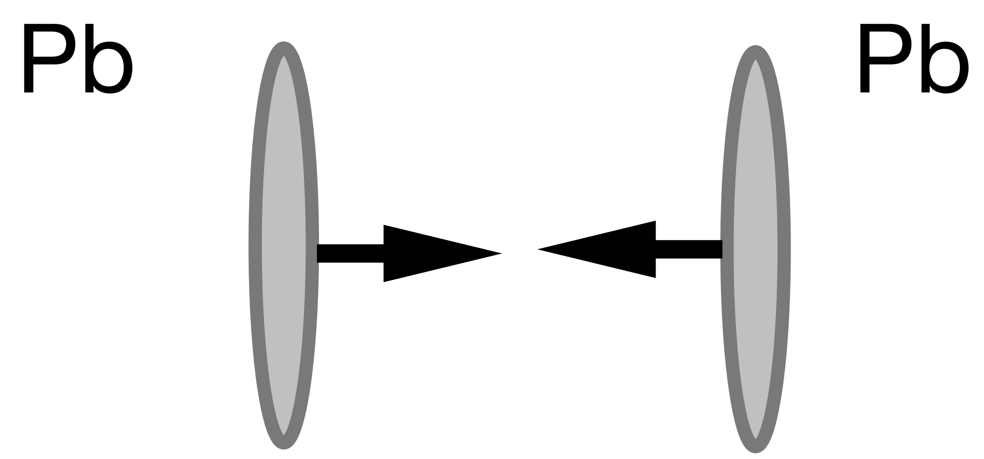
ALICE CERN-LHCC-2015-006

O2 Computing Farm

- Online Processing of all events
- Relevant for experiments at LHC, FAIR

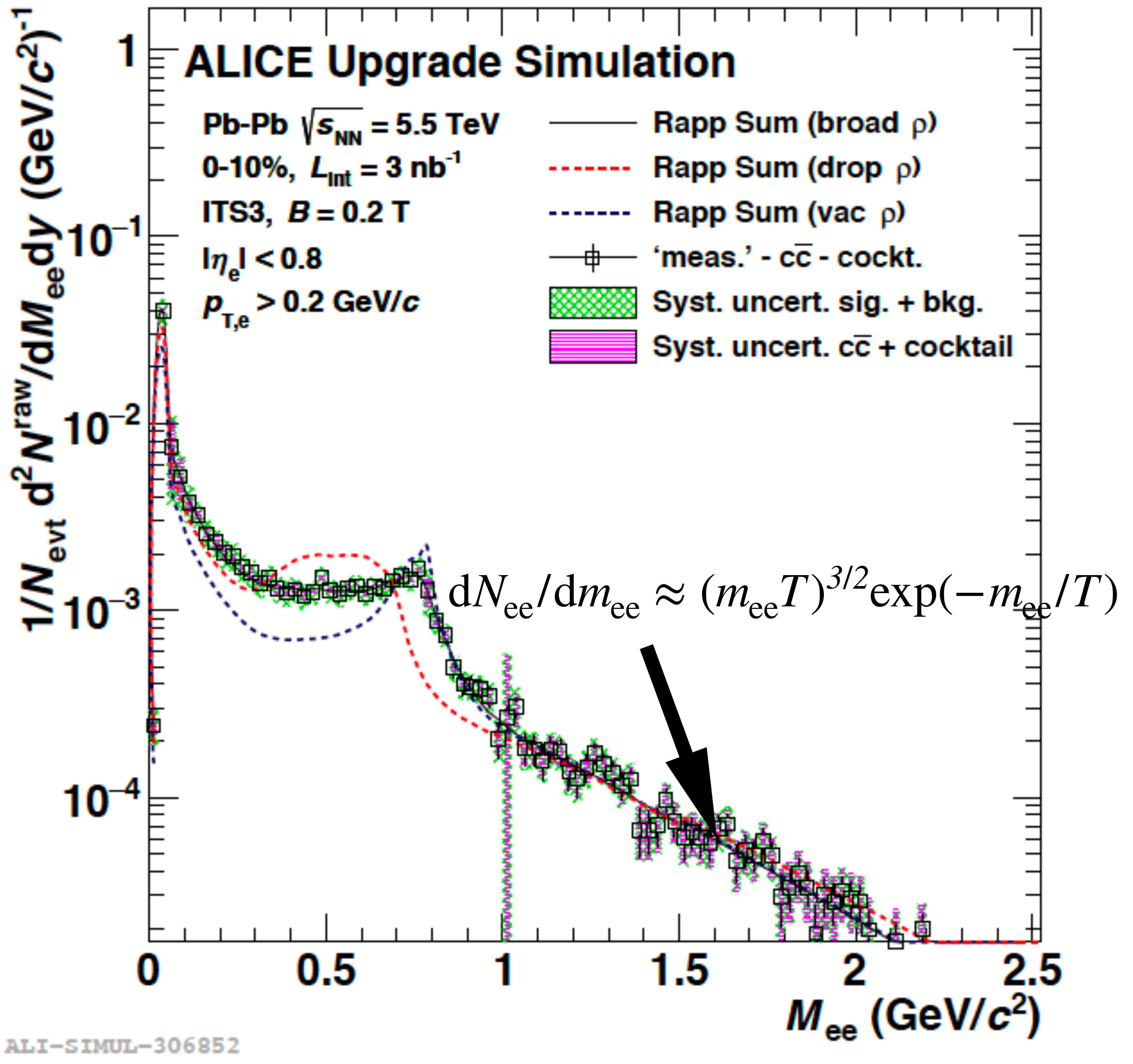
More upgrades done/planned…

Physics prospects Runs 3 & 4



Z. Citron et al CERN-LPCC-2018-07

Excess m_{ee} spectrum over cocktail in Run 4

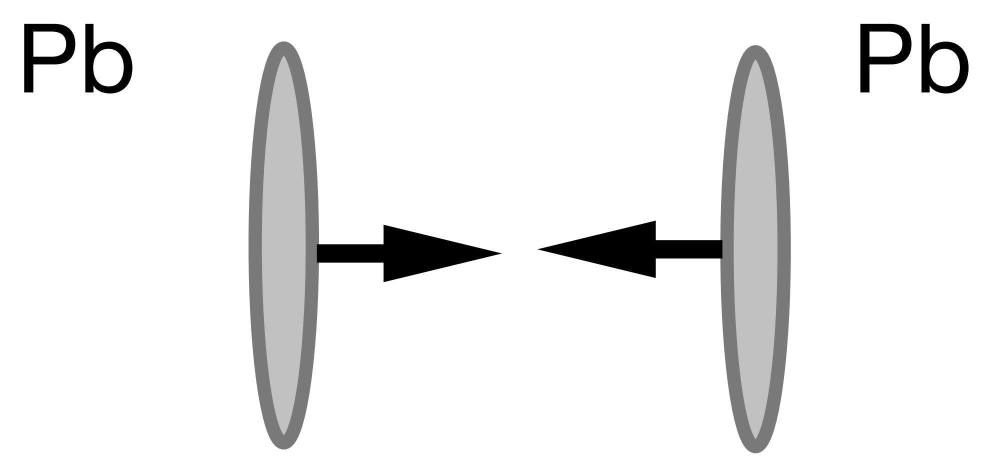


- Suppress HF hadron decays with max DCA_{ee} cut
- Expected signal after subtraction of hadronic cocktail and remaining background from correlated HF

At the end of Run 4:

- First time-averaged *T* of the QGP
- Patterns indicative of chiral symmetry restoration

Physics prospects Runs 3 & 4



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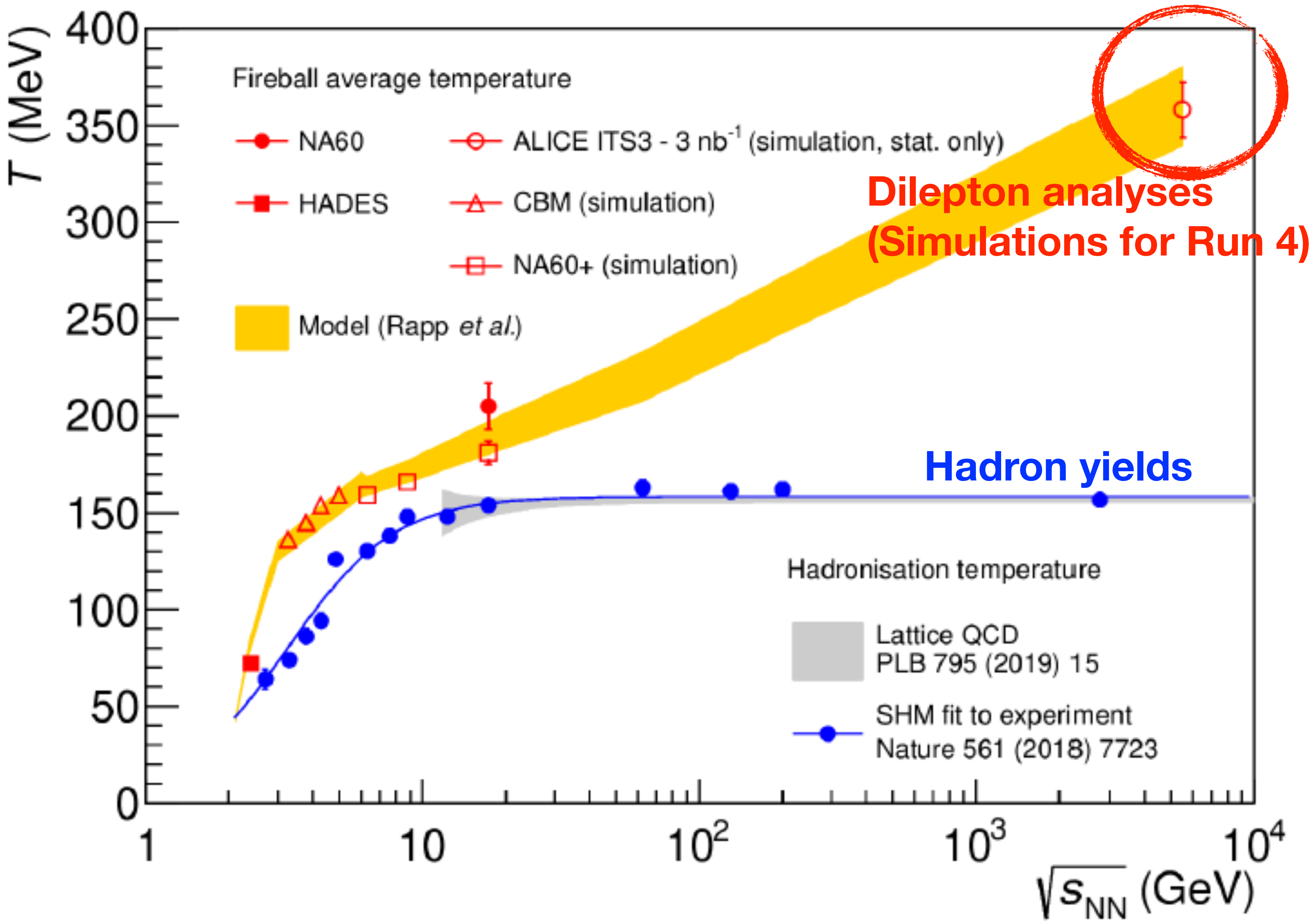
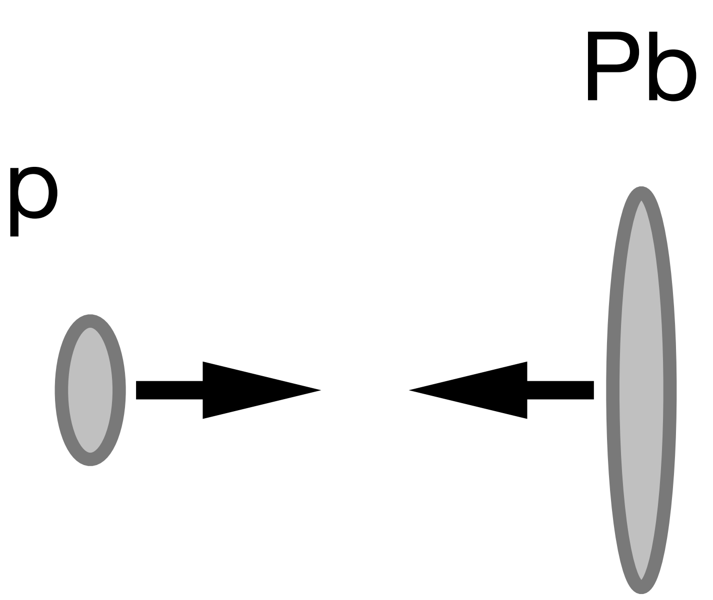


NA60, AIP Conf.Proc. 1322 (2010) 1, 1-10
HADES, Nature Physics 15 (2019) 10, 1040-1045
ALICE, CERN-LHCC-2019-018
CBM, Nucl. Phys. A 982 (2019) 163
NA60+, SPSC-EOI-019
R. Rapp et al., Phys. Lett. B 753 (2016) 568
T. Galatyuk et al., Eur. Phys. J. A52 (5) (2016) 131
Lattice QCD, Phys. Lett. B 795 (2019)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

Physics prospects Runs 3 & 4



- Extensive programme with smaller systems: high-multiplicity pp, pPb, pO, OO collisions

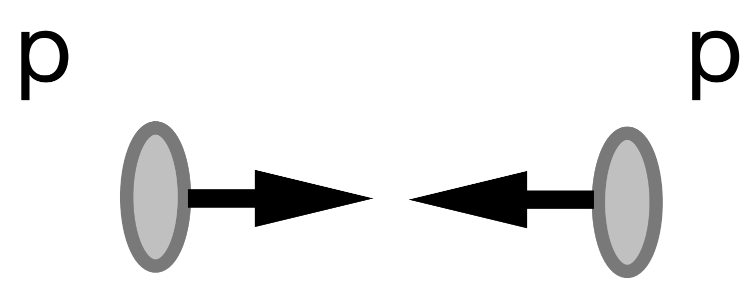
- From Runs 1 & 2 measurements in small systems:
  - Flow signals ($v_2 > 0$) observed
  - Smooth increase of strangeness with event multiplicity
  - But no quenching (energy loss) observed

$\rightarrow$ Search for on-set of thermal radiations in small systems

$\rightarrow$ Study ρ spectral function in pp collisions with high local baryon density

Z. Citron et al CERN-LPCC-2018-07

Physics prospects Runs 3 & 4

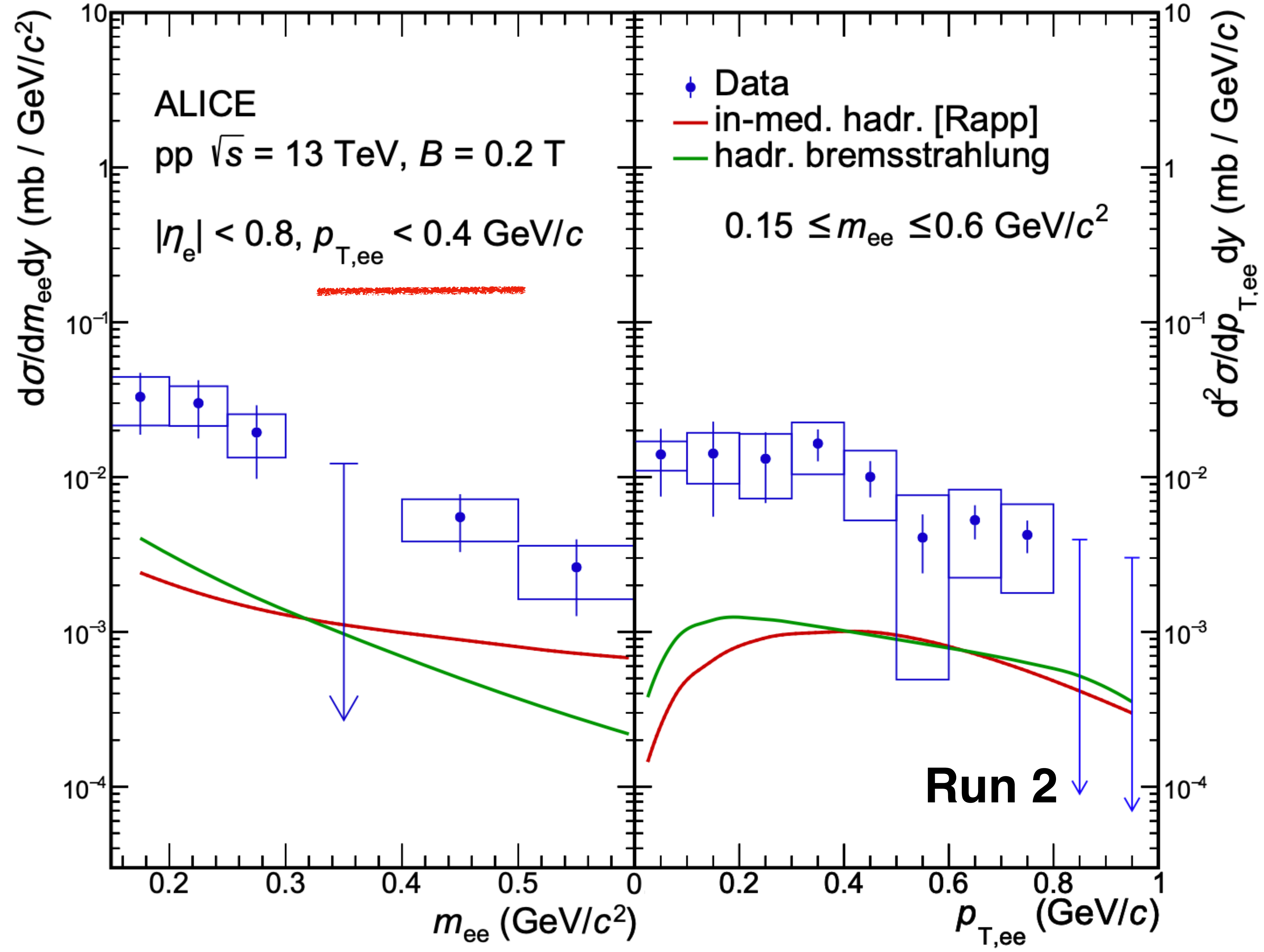


- Excess of soft γ and l^+l^- in hadron-hadron collisions at lower $\sqrt{s}$ observed by several experiments

- Unique sensitivity to soft e^+e^- at the LHC with ALICE
  dedicated runs with lower *B* field in the central barrel
  → **Excess also observed at the LHC in pp at $\sqrt{s}$ = 13 TeV**
  Not described by thermal radiation/hadronic bremsstrahlung

Increase statistics by a factor 400 in Runs 3 + 4
→ Allows precise multi-differential analysis

Excess e^+e^- spectra
pp collisions at $\sqrt{s}$ = 13 TeV



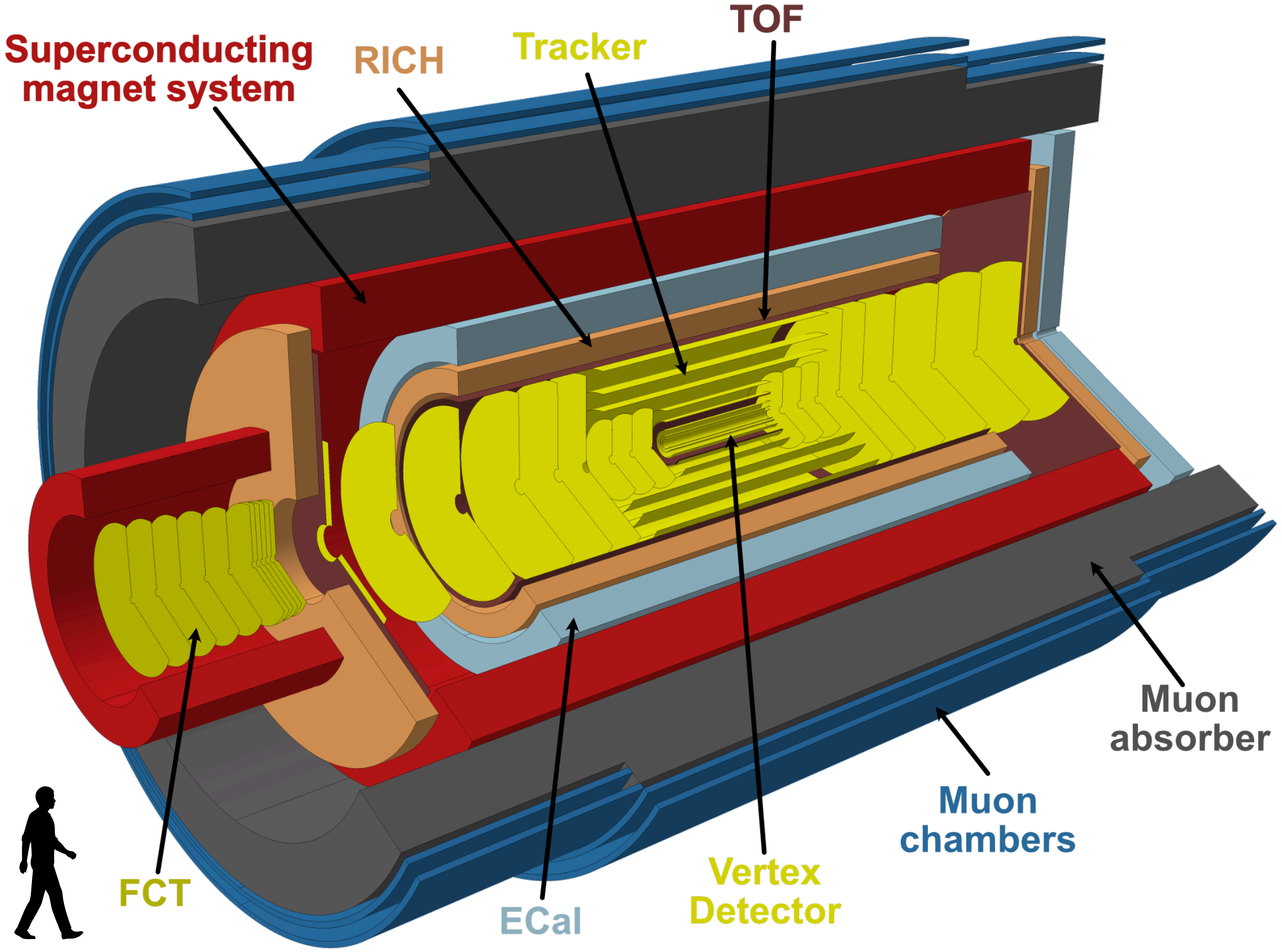
ALICE Phys. Rev. Lett. 127 (2021) 042302

V. Hedberg PhD thesis, Lund (1987); DLS Collaboration, Phys. Rev. Lett. 61 (1988) 1069-1072; M.R.Adams *et al.* Phys, Rev. D27 (1983) 1977-1998; K.J. Anderson *et al.* Phys. Rev. Lett 37 (1976) 700-802; A.Belogianni *et al.* Phys.Lett. B548 no. 3 (2002) 122-128,129-130; J.Antos et al. Z. Phys. C59 (1993) 547-554

Beyond Run 4: ALICE 3

- Compact all-silicon tracker with high-resolution vertex detector

- Particle identification $\gamma, e^{\pm}, \mu^{\pm}, K^{\pm}, \pi^{\pm}$
  - Over large acceptance $(-4 < \eta < 4)$
  - Down to very low p_T

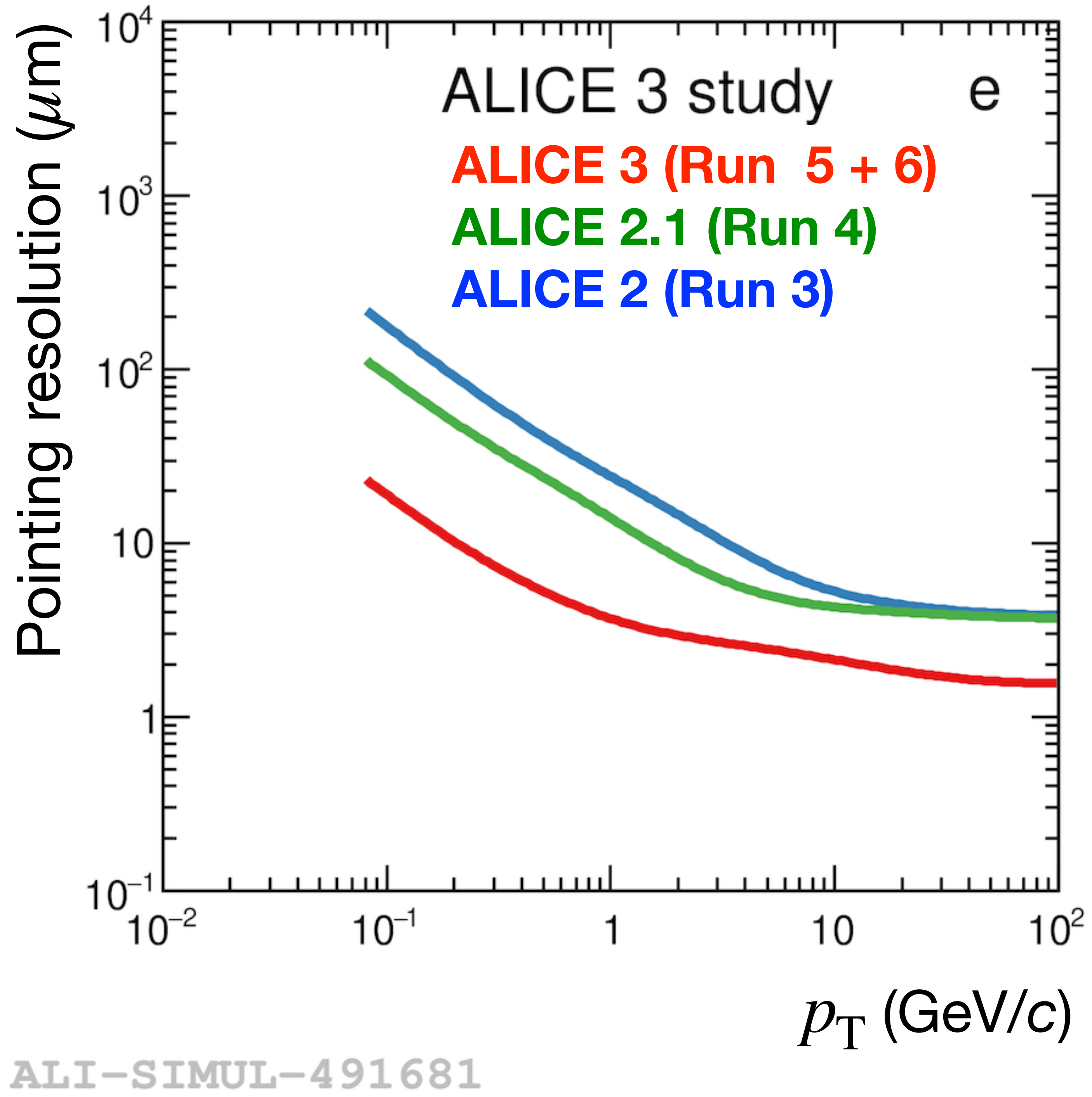


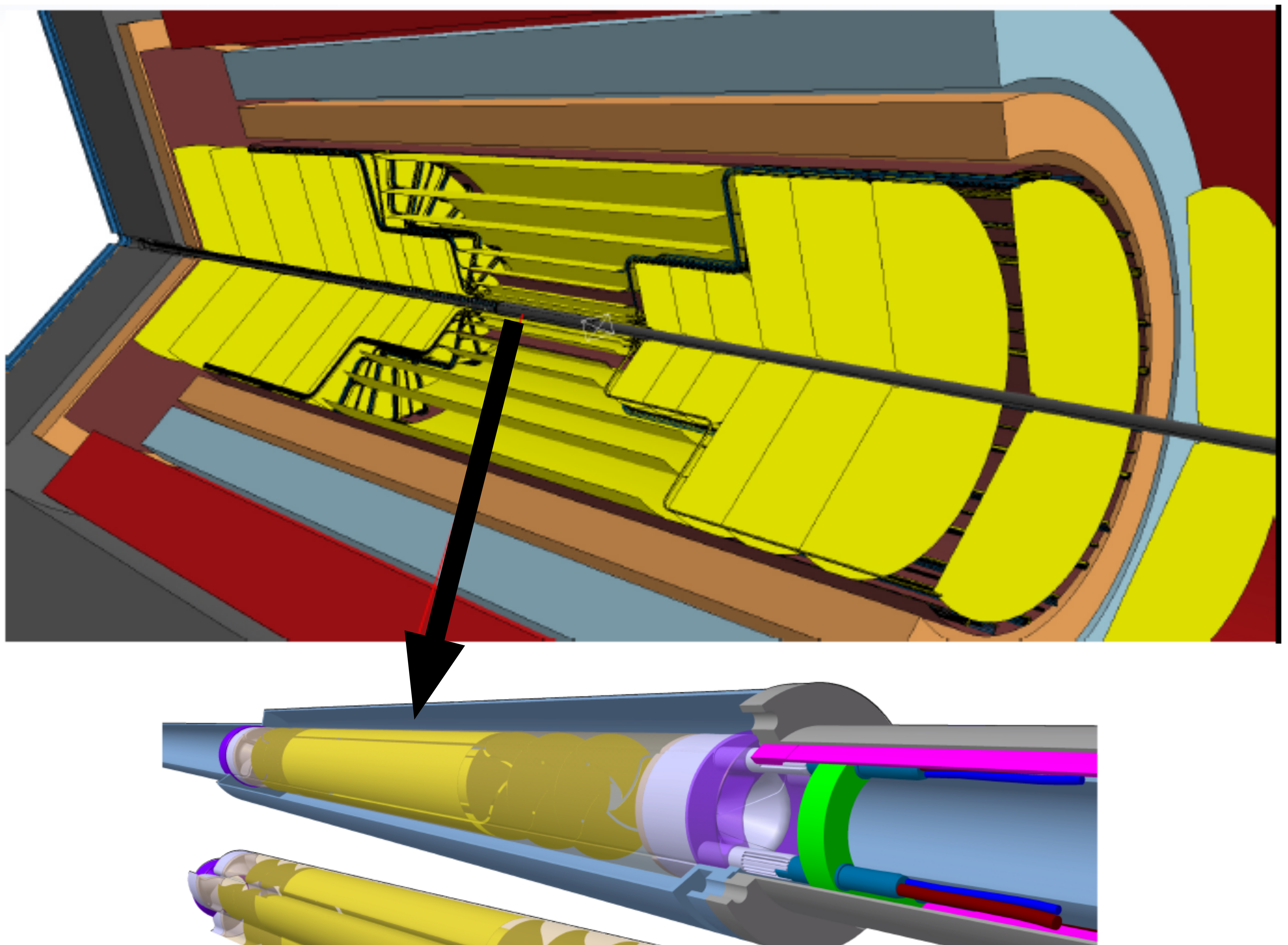
D.Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009

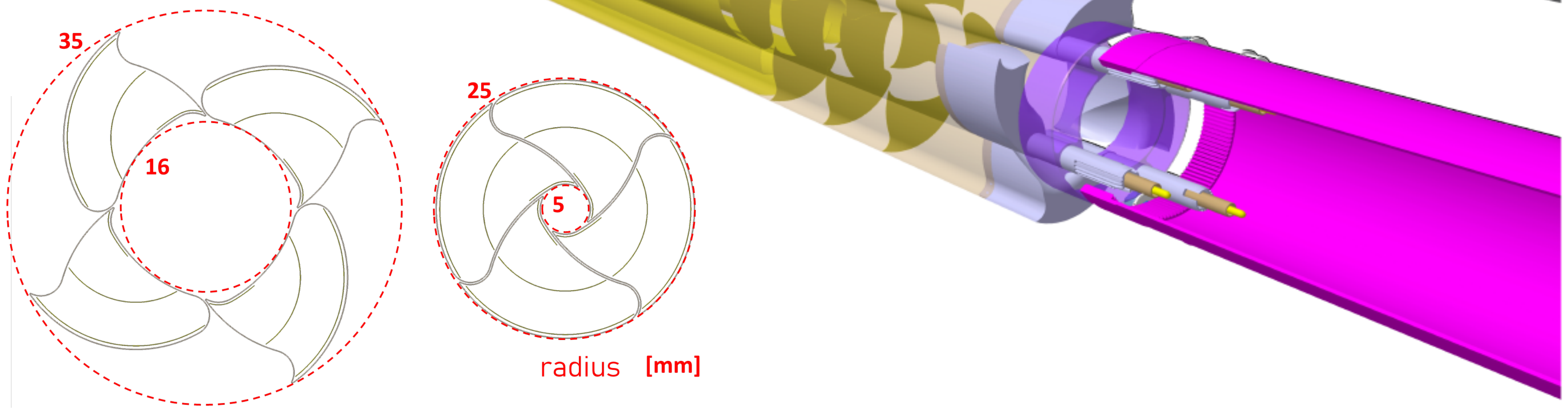
Tracker

- Position of first layer at mid-rapidity:
  $r = $ **5 mm** (ALICE Run 4: 18 mm; ALICE Run 3: 22mm)

- Achieved with a retractable vertex detector inside of the beam pipe in secondary vacuum





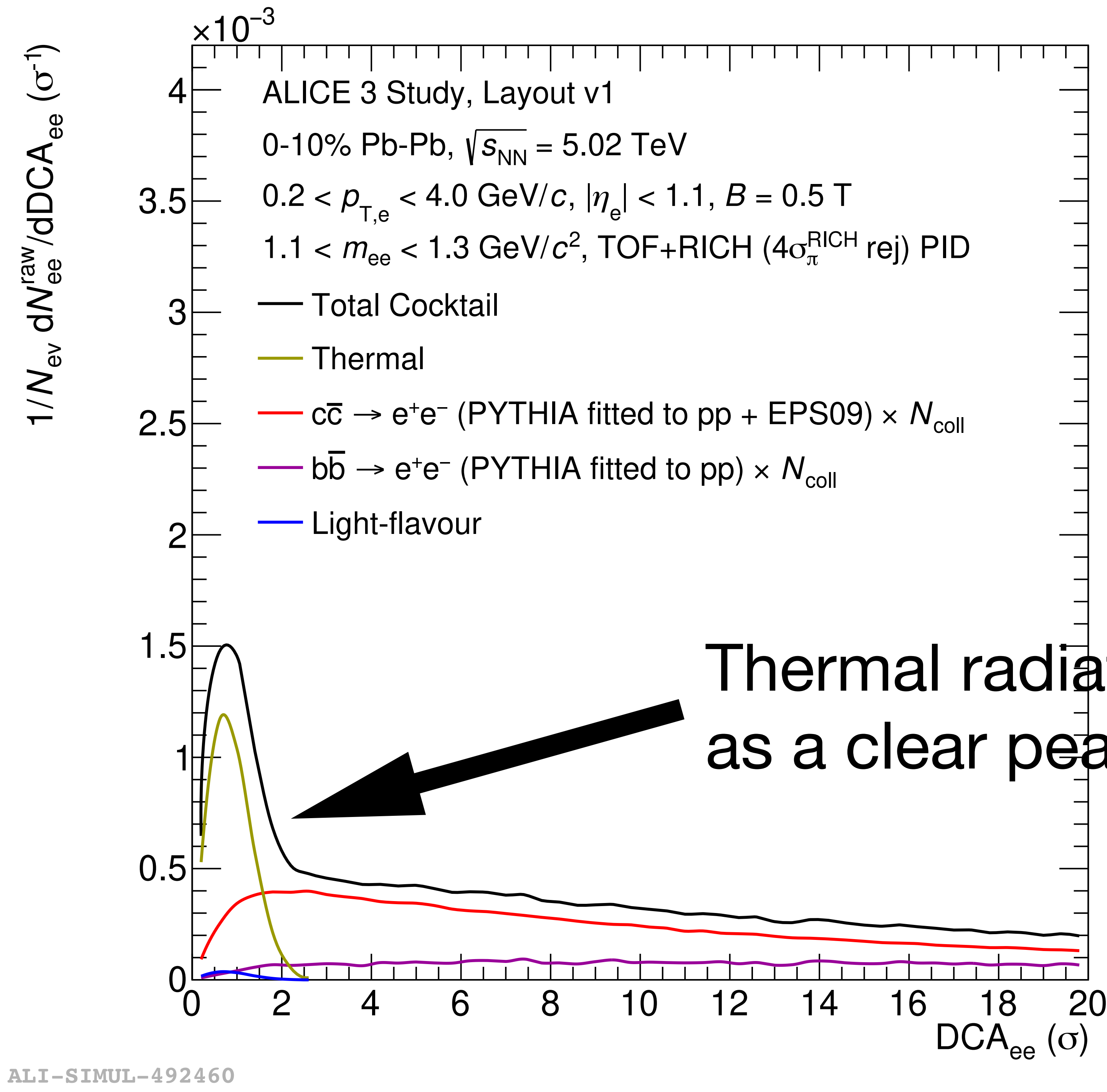


ALICE CERN-LHCC-2022-009

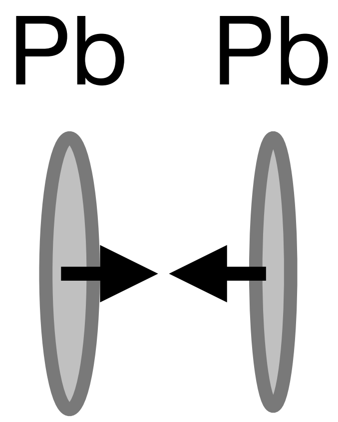
Tracker

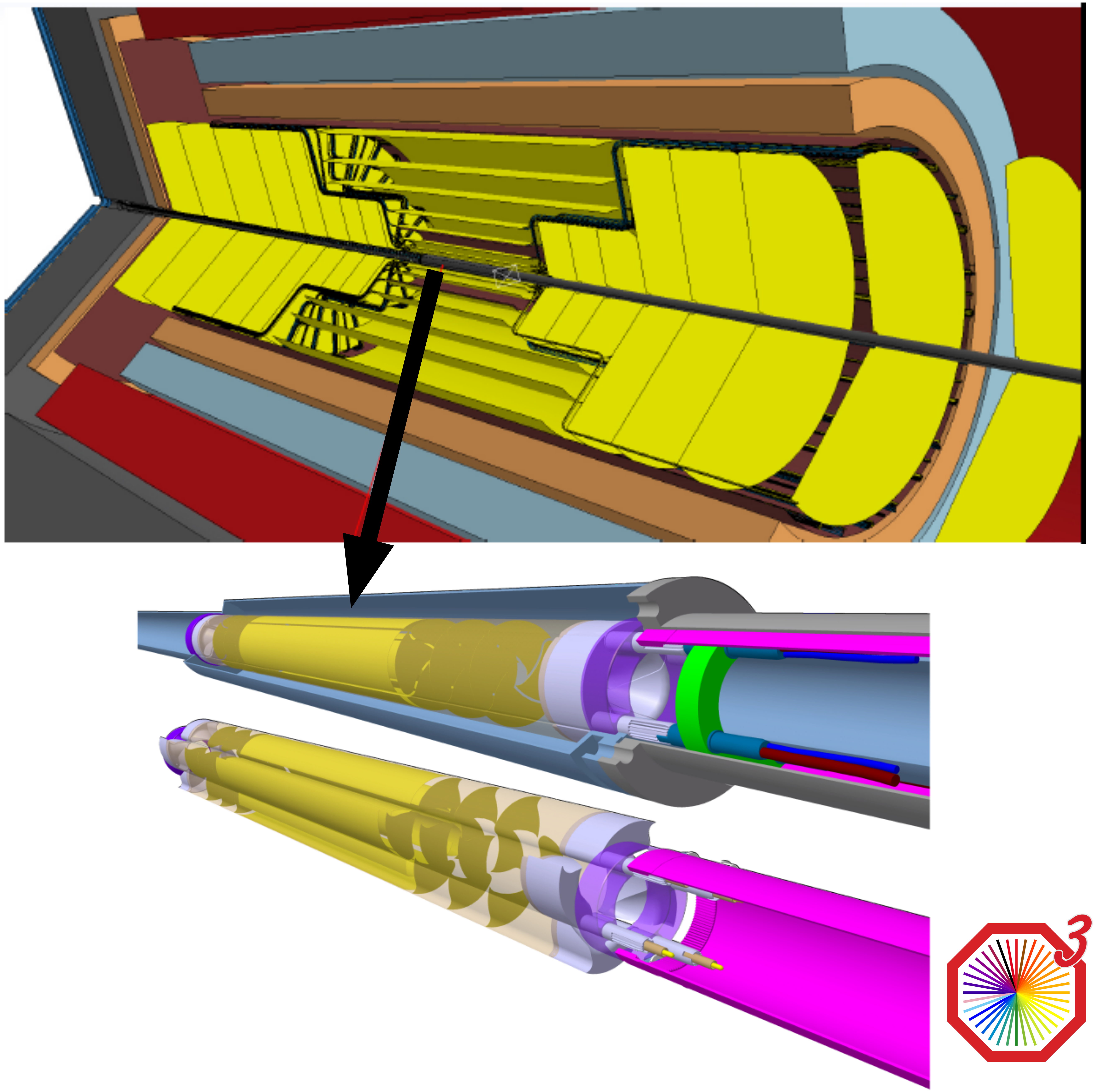
- Position of first layer at mid-rapidity:
  $r = $ **5 mm** (ALICE Run 4: 18 mm; ALICE Run 3: 22mm)
- Achieved with a retractable vertex detector inside of the beam pipe in secondary vacuum

Expected DCA$_{ee}$ distribution in IMR



Thermal radiation seen as a clear peak at small DCA$_{ee}$

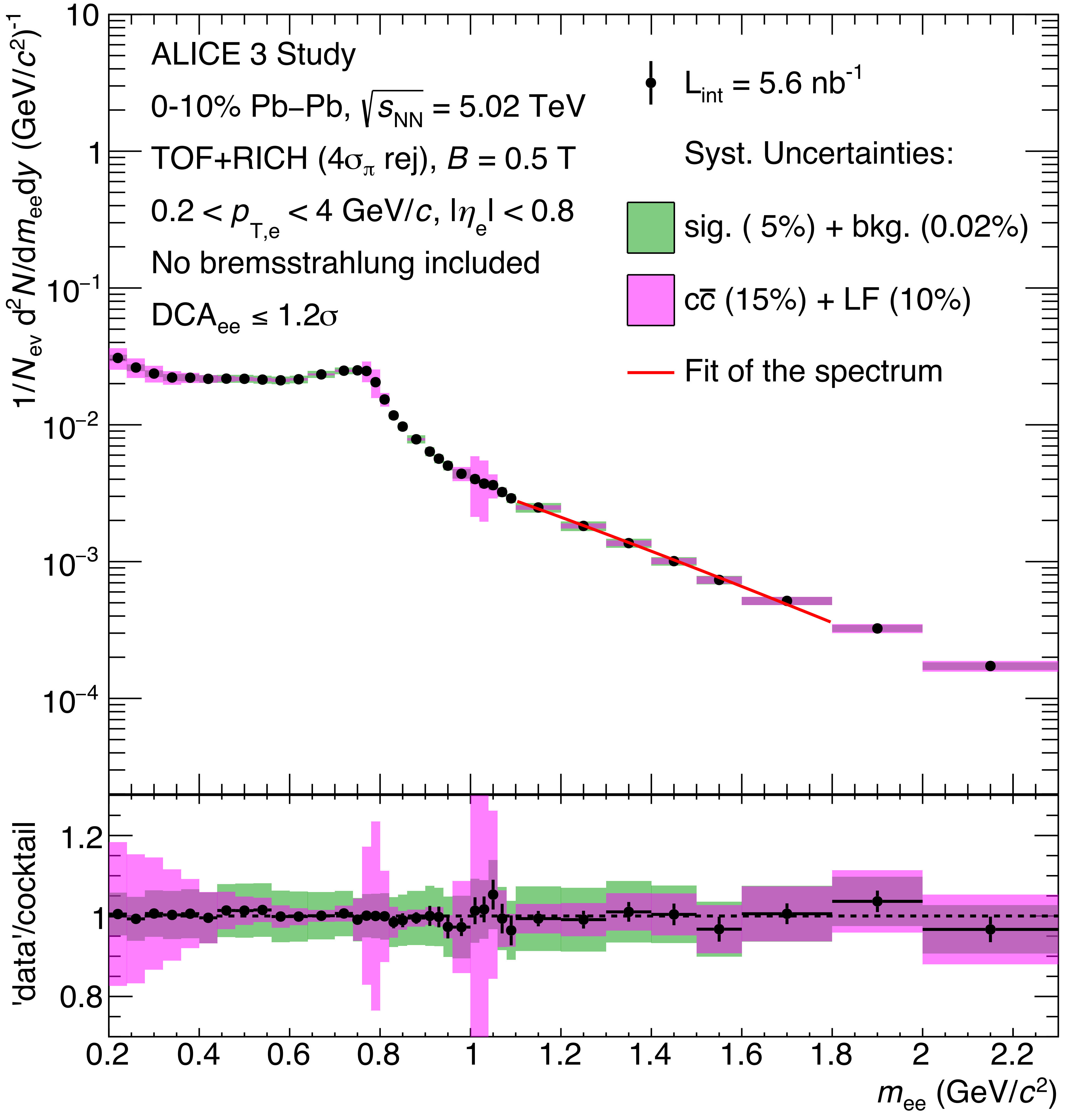


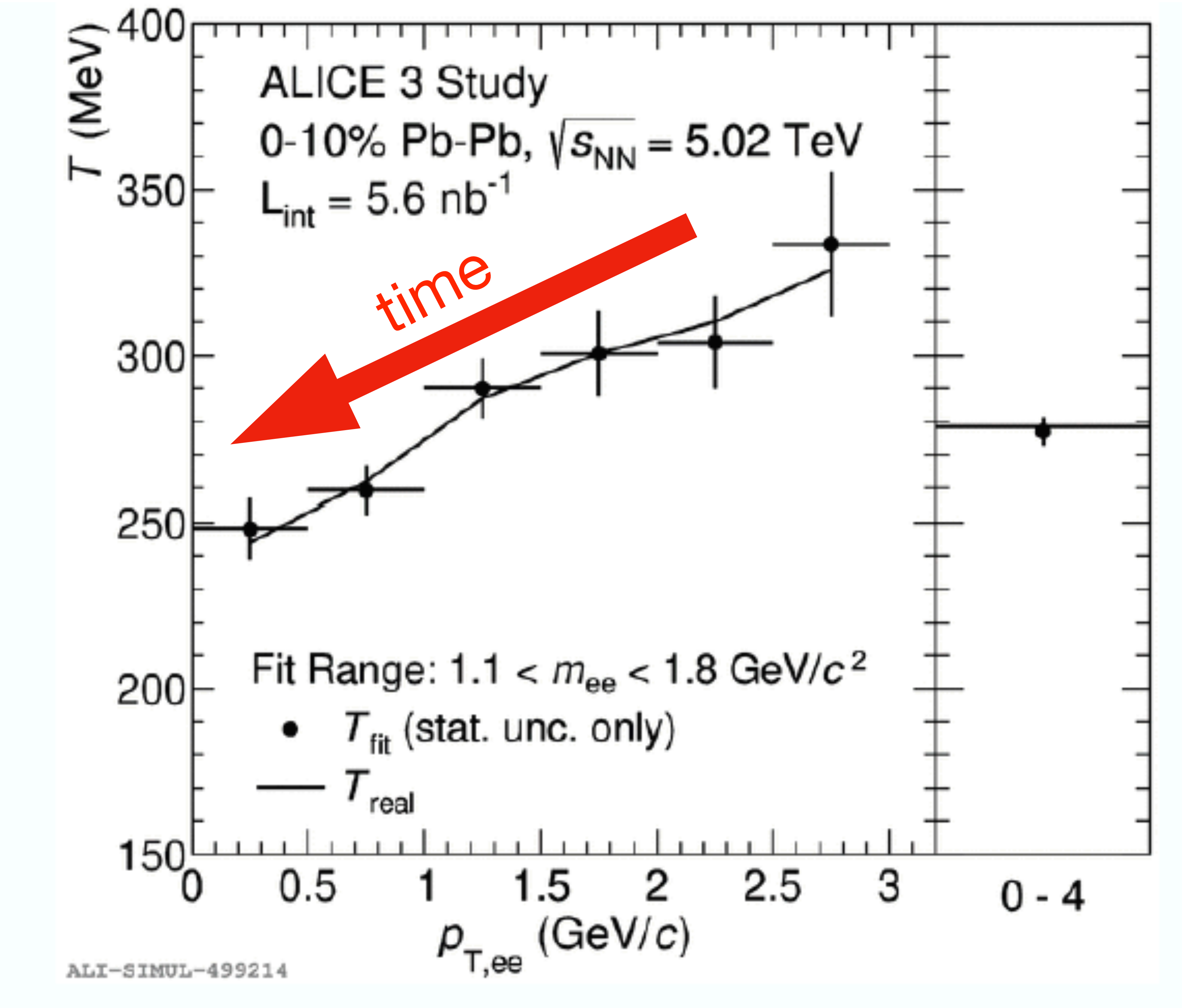


ALICE CERN-LHCC-2022-009

Time dependence of early temperature

Expected excess m_{ee} spectrum with ALICE 3



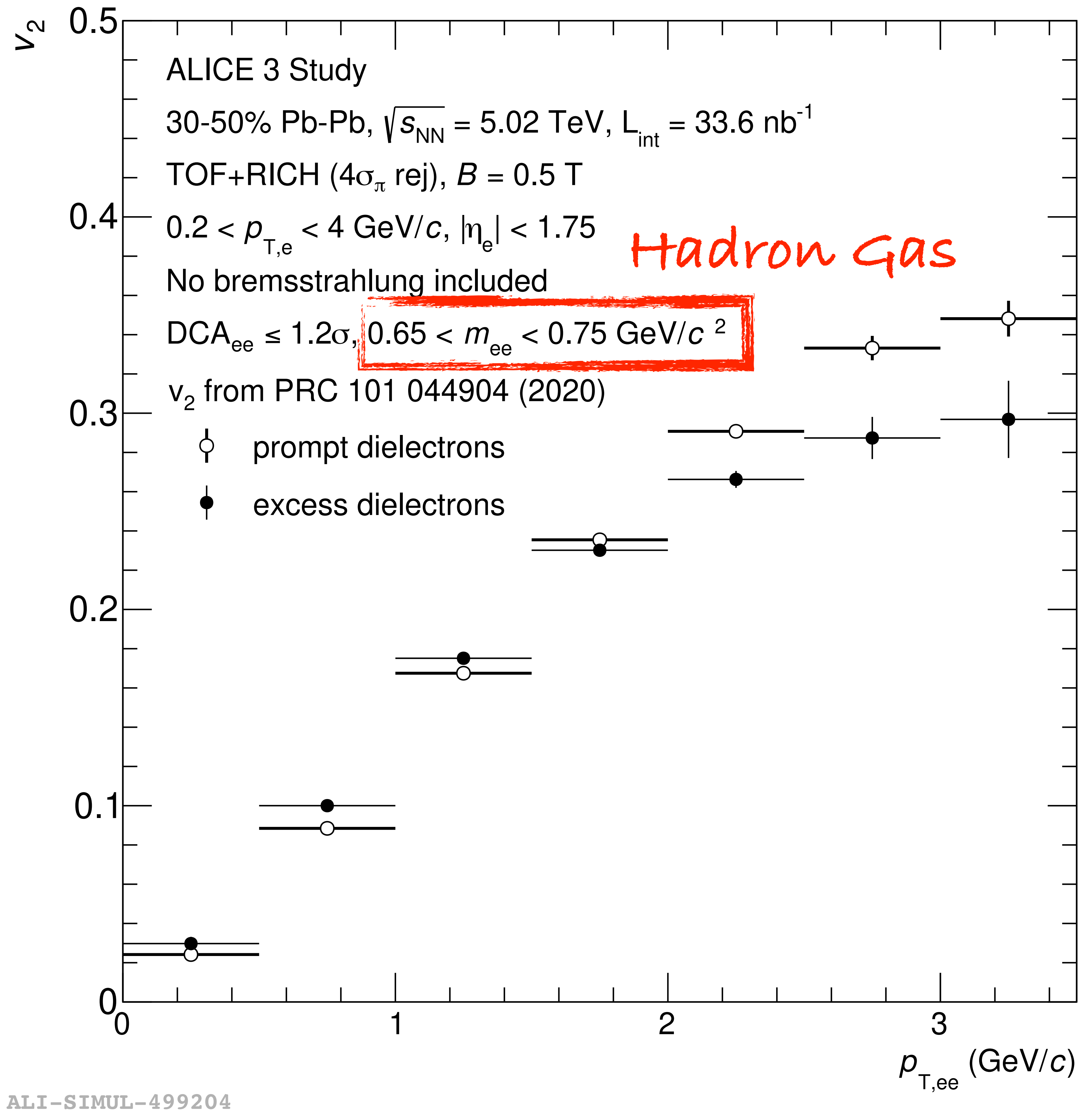


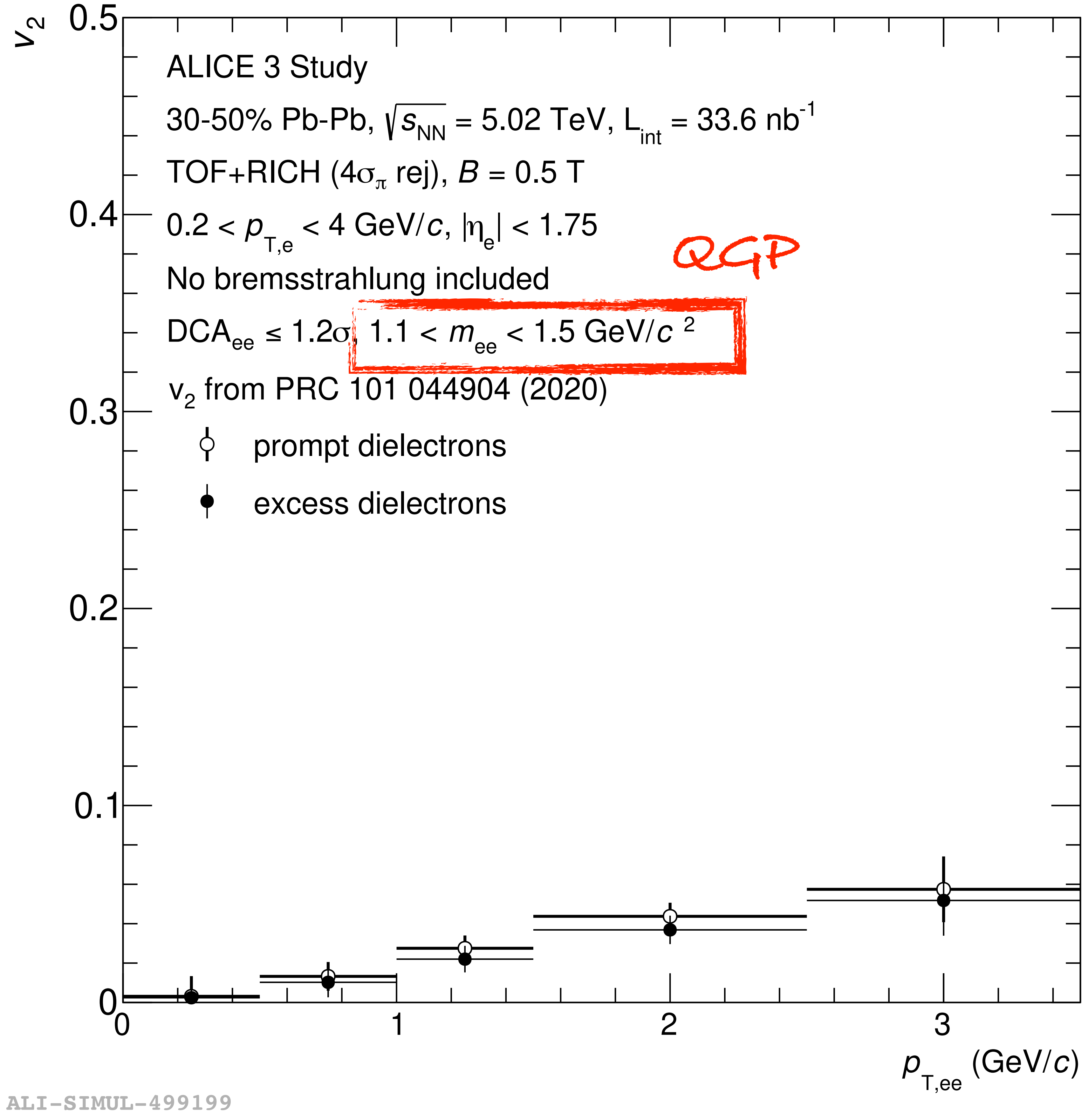
Fit of m_{ee} spectrum → Average temperature

Fit for different $p_{T,ee}$ windows → Probe time dependence of T

Time dependence of elliptic flow

Projection for dielectron v_2 in mass regions with dominant thermal contributions



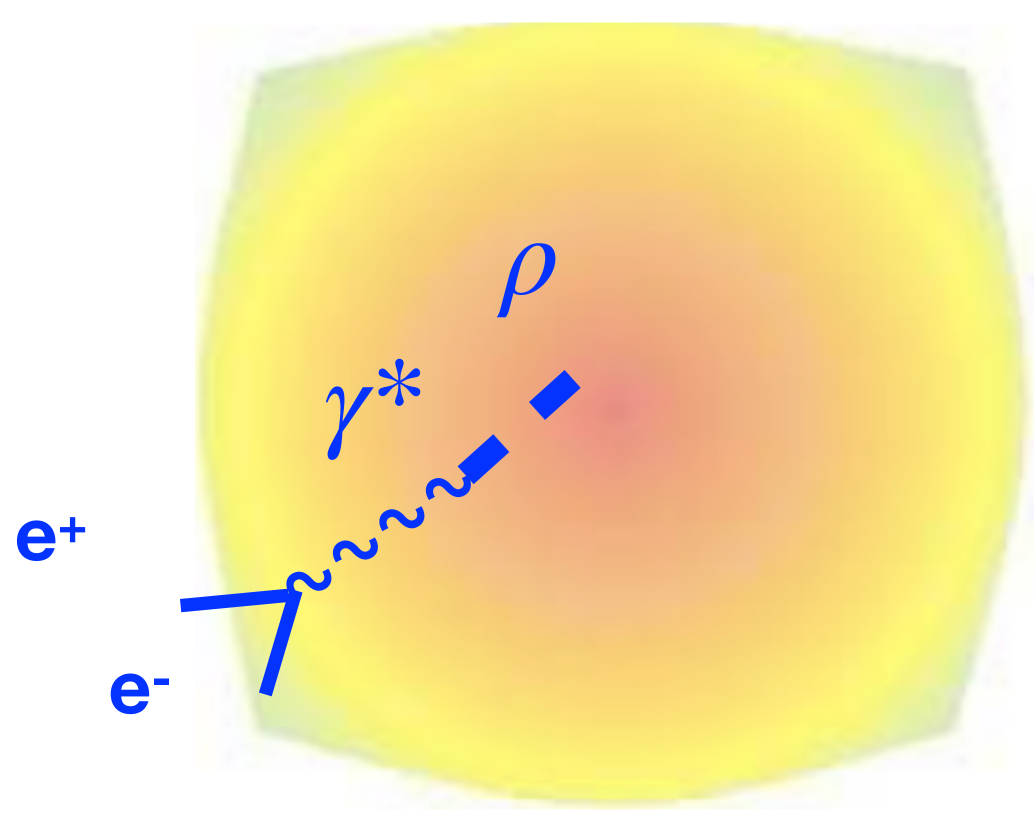


Statistical significant measurements possible

→ Study time evolution of flow field (crucial to understand γ_{dir} yield&v_2)

Chiral symmetry restoration

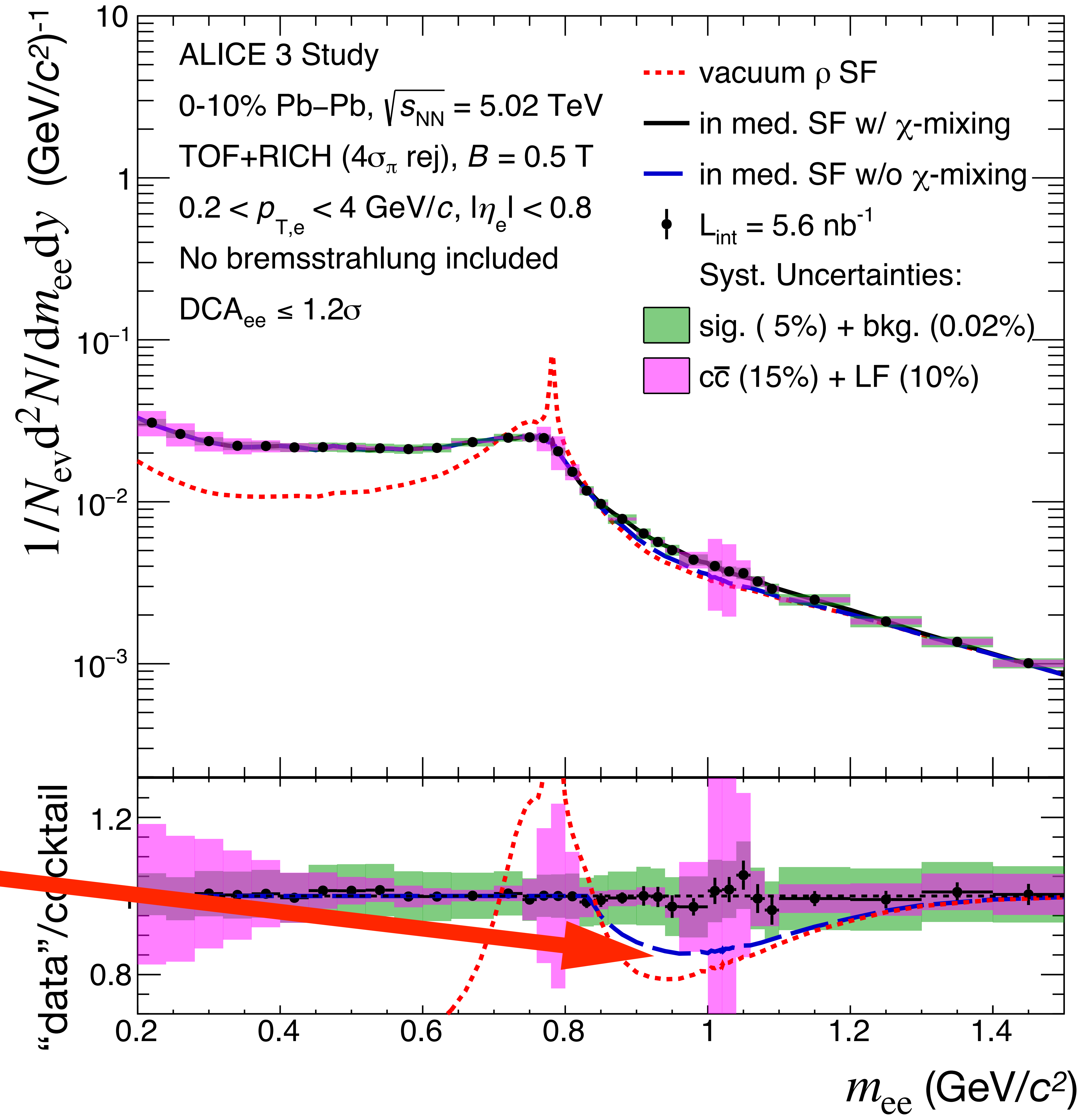
Hot hadron gas



High precision measurement of ρ spectral function with ALICE 3

Access to chiral symmetry restoration mechanisms like $\rho - \mathrm{a}_1$ mixing

Expected excess m_{ee} spectrum with ALICE 3



R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
ALICE CERN-LHCC-2022-009

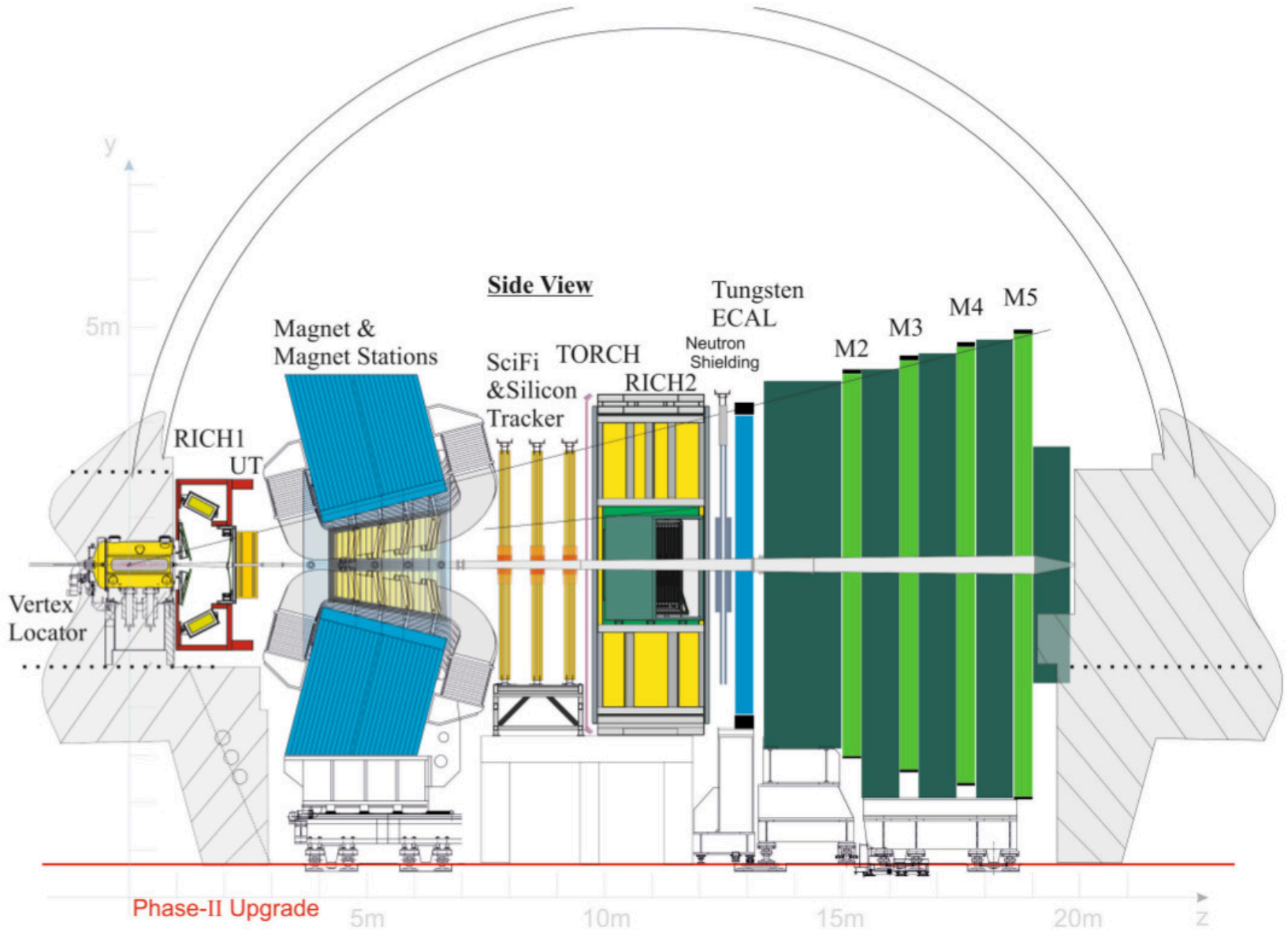
LHCb Upgrade II: Run 5 and beyond

CERN-LHCC-2021-012

Should allow LHCb to take data also **in central AA collisions** !

with excellent vertexing capabilities

and relatively low momentum $e^{\pm}$ identification capabilities



Complementary to ALICE 3 in the $2 < y < 5$ rapidity range

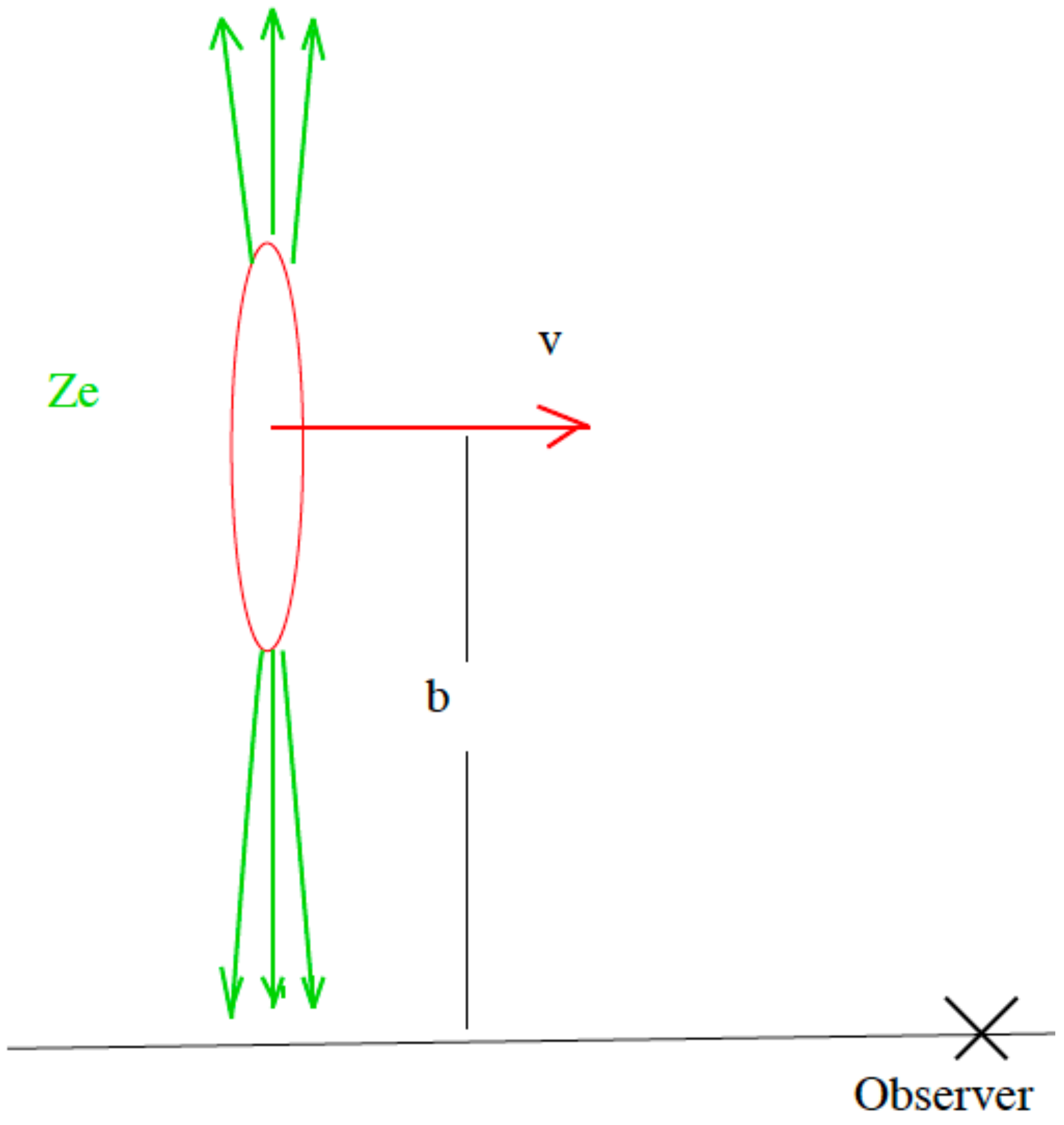
Focus 2: two-photon interactions

Electromagnetic fields in heavy-ion collisions

Strong electromagnetic (EM) fields
produced by the Lorentz-contracted nuclei (up to 10^{15} T):

- **Maximum electric field** $\approx Ze\gamma_L/b^2$
  γ_L Lorentz factor of the nuclei ($\gamma_L^{RHIC} \approx$ 100, $\gamma_L^{LHC} \approx$ 2700)
  $\rightarrow$ **x 30 larger at the LHC compared to RHIC**

- **Acts over a short timescale:** $b/(\gamma_L c)$
  $10^{-25}(20^{-23})$s at the LHC (RHIC)

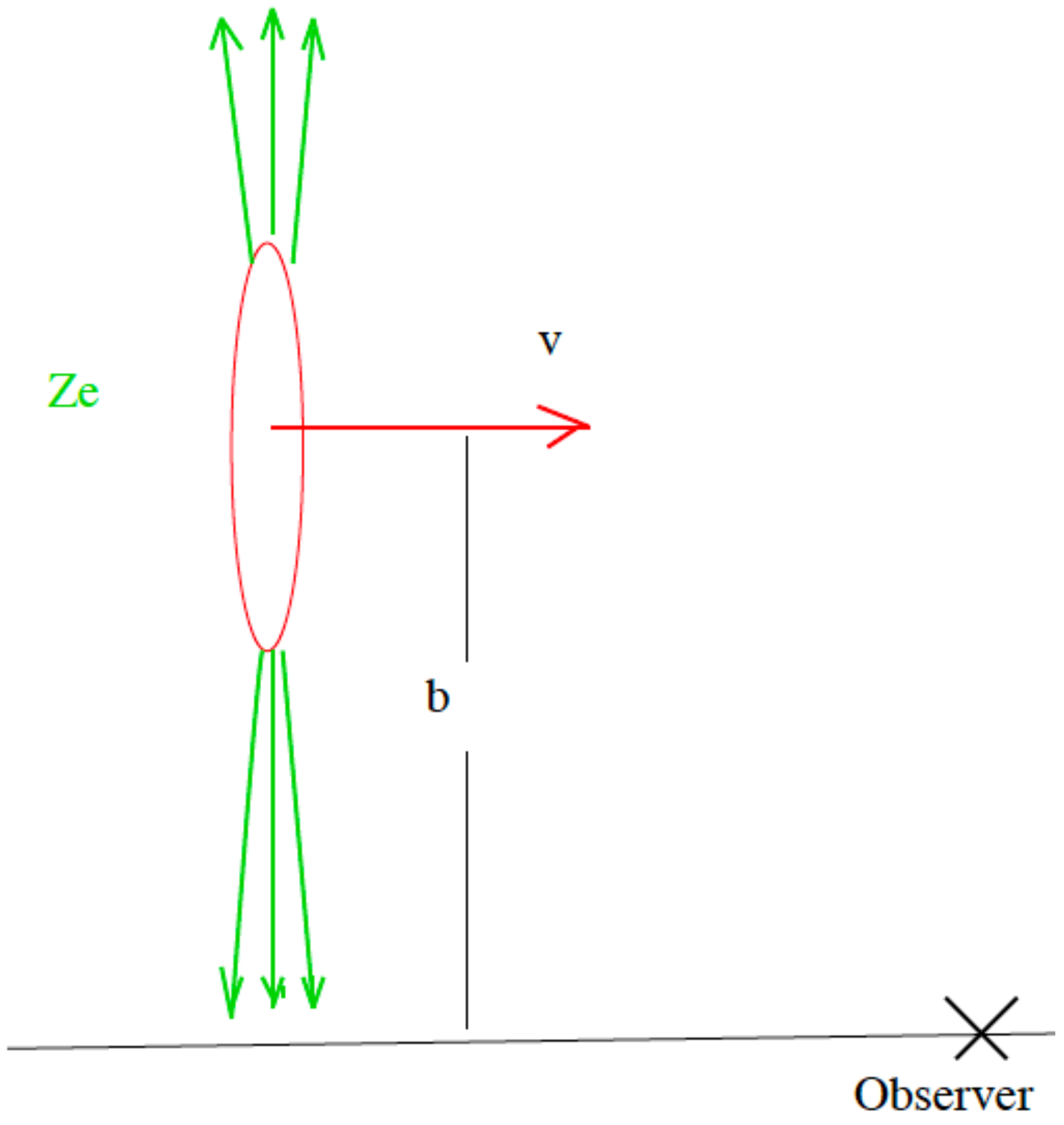


Equivalent Photon Approximation

Fermi, Landau, von Weizsäcker, Williams

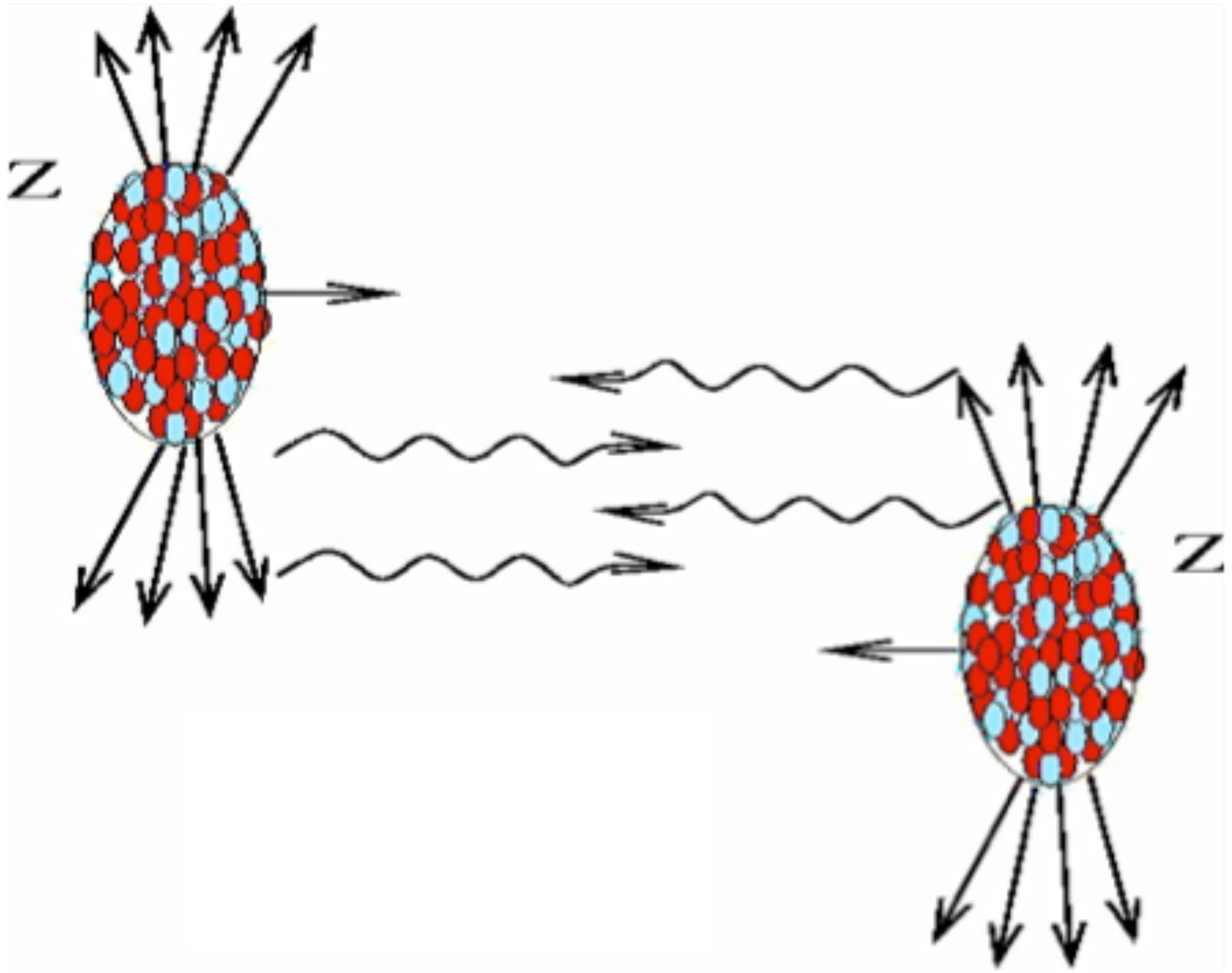
Strong electromagnetic (EM) fields
→ **Quasi-real photon flux** generated coherently

- **Coherent strengths** (rates) $\propto Z^2$
- **Maximum energy** $E_{\gamma,\max} \approx \gamma_L(\hbar c/R)$
  80 GeV in Pb—Pb at the LHC
  3 GeV in Au—Au at RHIC
- **Typical** p_T **(& virtuality)** $p_{T,\max} \approx \hbar c/R$
  O(30) MeV at RHIC and LHC

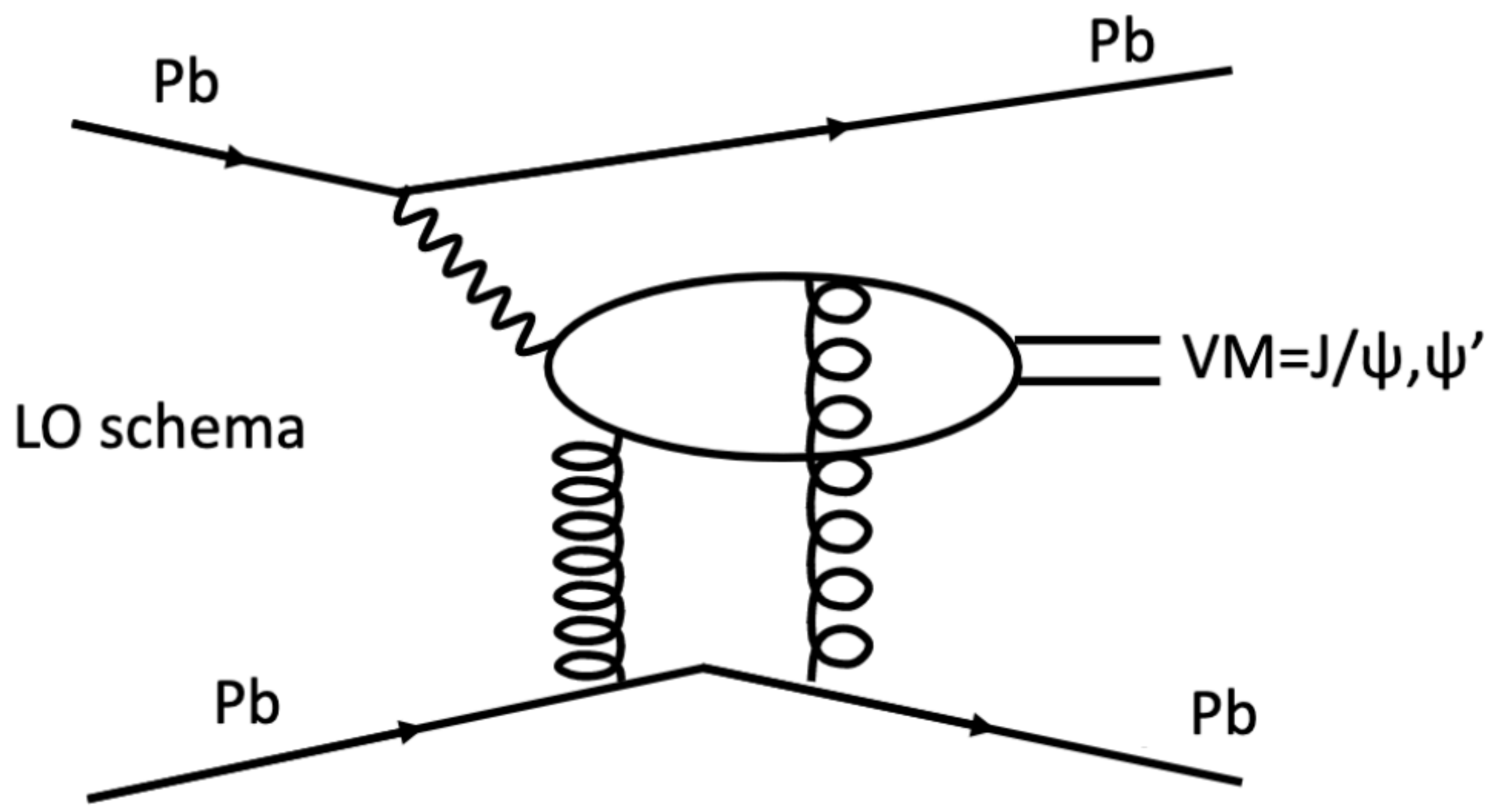


R charge radius of nucleus

Photon induced processes in heavy-ion collisions

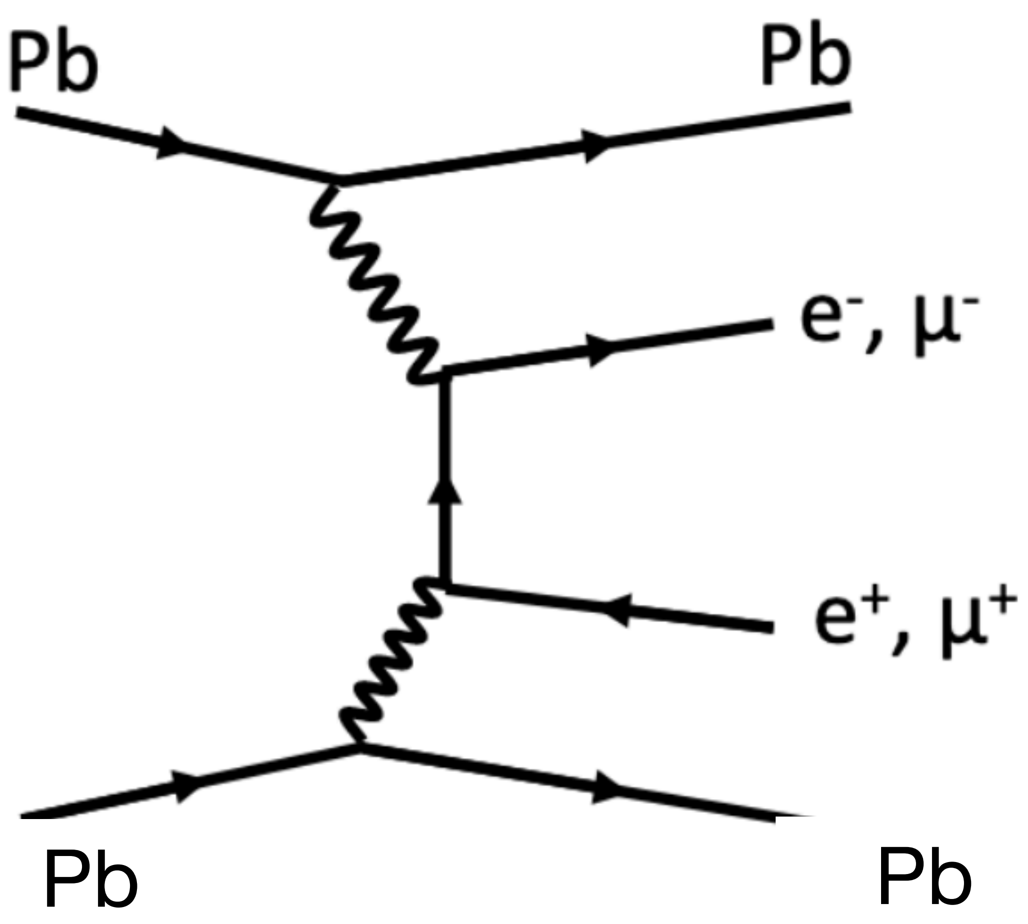


Production of vector mesons



→ Access to gluon distributions in nucleus

Dilepton production

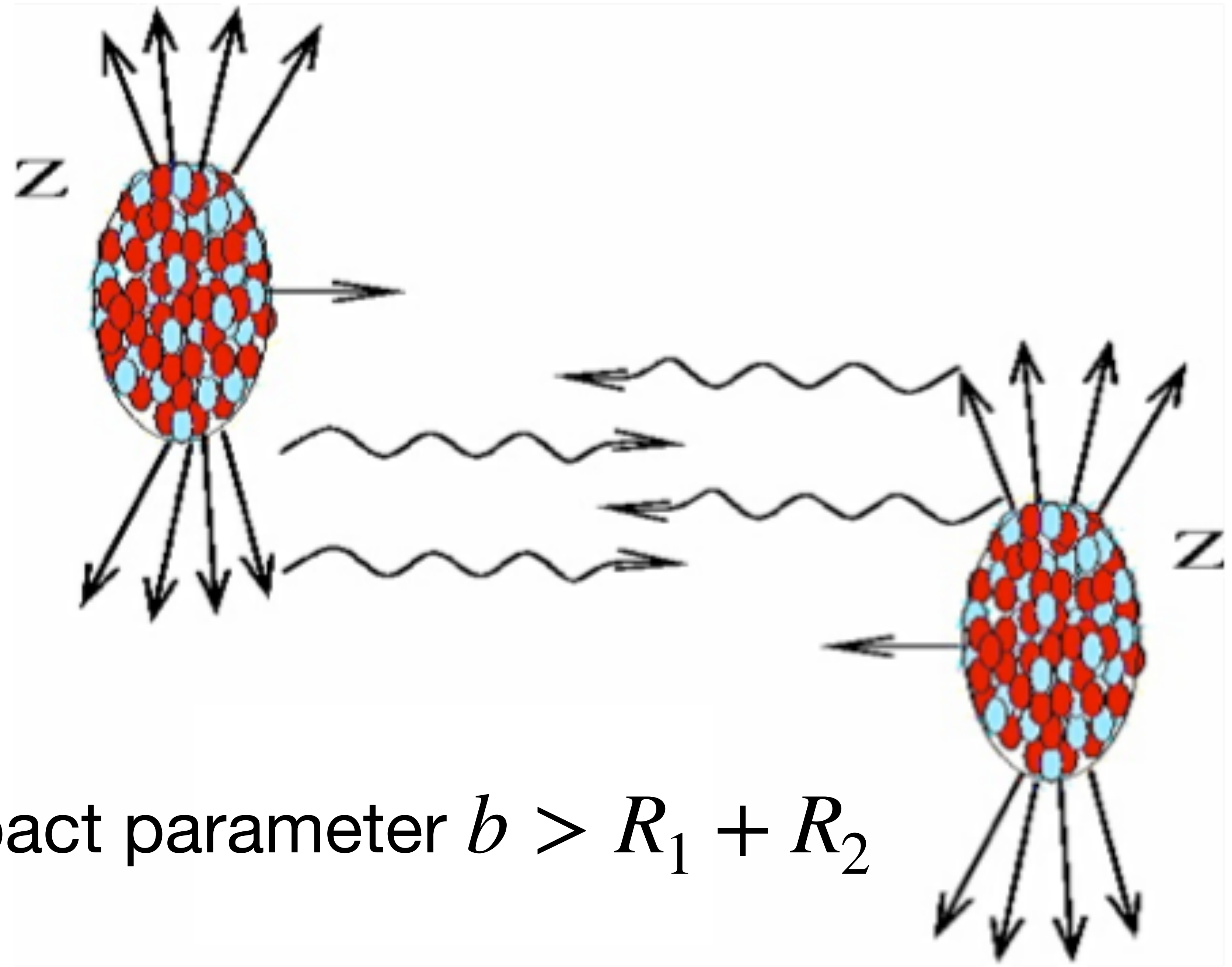


→ test QED, map EM field

Concentrate here on dilepton production

(Breit-Wheeler process)

$\gamma\gamma \rightarrow l^+l^-$ in ultra-peripheral heavy-ion collisions



Impact parameter $b > R_1 + R_2$

Ultra-peripheral collisions (UPCs):
Clean environment without hadronic interaction

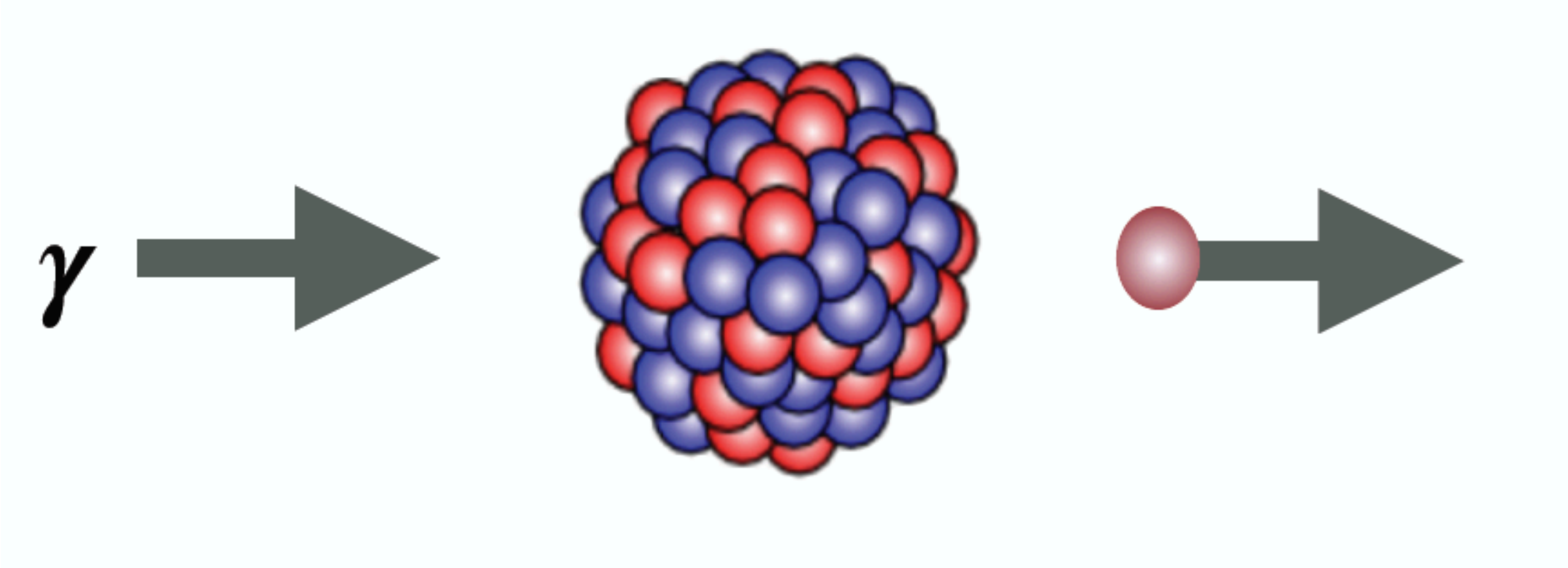
Runs 1+2 at the LHC:

- ALICE $\gamma\gamma \rightarrow e^+e^-$ Pb—Pb at $\sqrt{s_{NN}} = 2.76$ TeV
  $4 < m_{e^+e^-} < 10$ GeV/c^2 ALICE Eur. Phys. J. C 73 (2013) 2617
  Capabilities to go even lower in $m_{e^+e^-}$
- ATLAS $\gamma\gamma \rightarrow \mu^+\mu^-$ Pb—Pb at $\sqrt{s_{NN}} = 5.02$ TeV
  $10 < m_{\mu^+\mu^-} < 80$ GeV/c^2 ATLAS Phys. Rev. C 104, 024906 (2021)
  $5 < m_{e^+e^-} < 90$ GeV/c^2 QM2022 ATLAS preliminary
- CMS $\gamma\gamma \rightarrow e^+e^-$ Pb—Pb at $\sqrt{s_{NN}} = 5.02$ TeV
  $5 < m_{e^+e^-} < 100$ GeV/c^2 CMS Phys. Lett. B 797 (2019) 134826,
  $8 < m_{\mu^+\mu^-} < 60$ GeV/c^2 CMS Phys. Rev. Lett 127 (2021) 122001

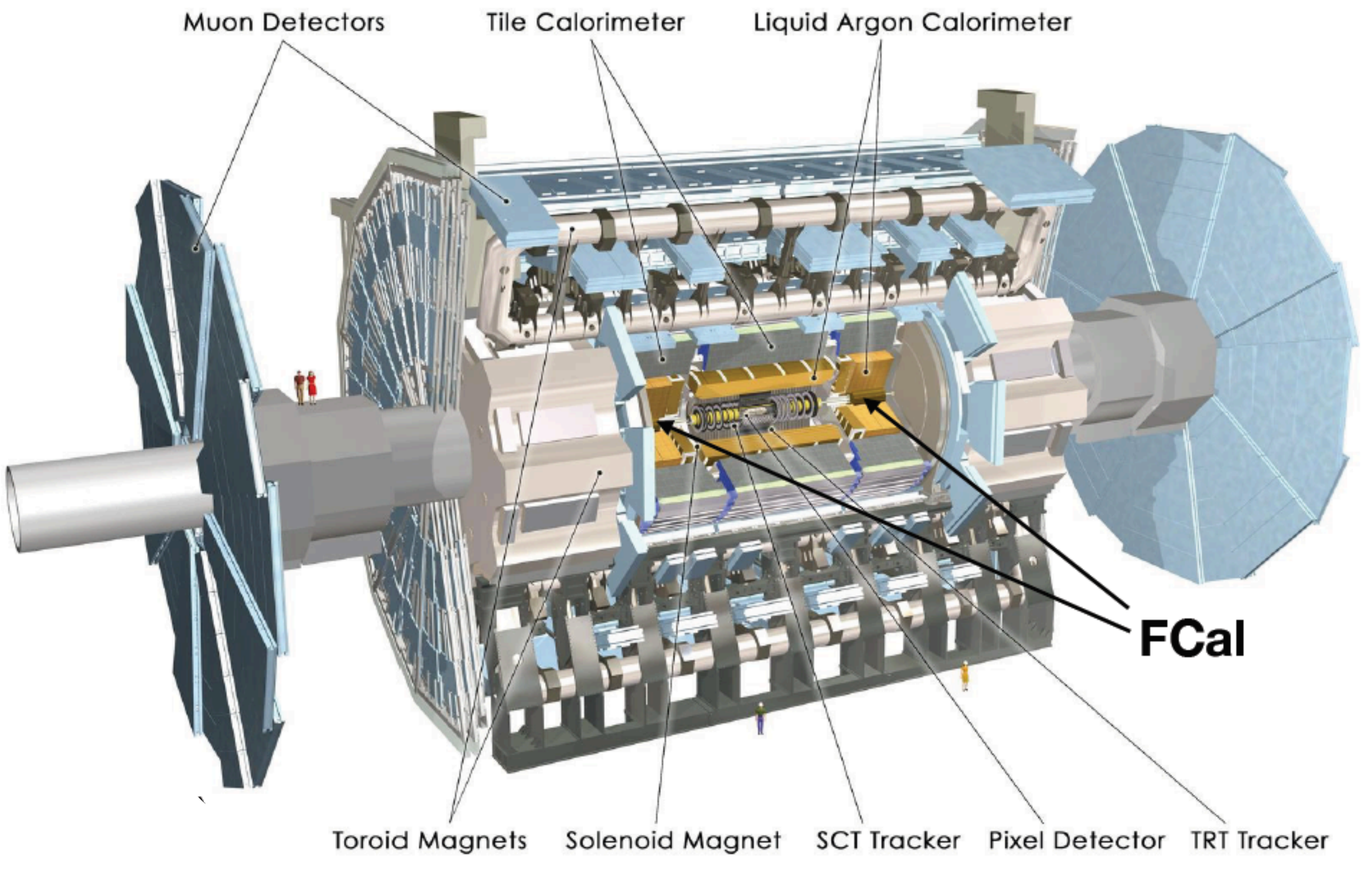
Varying impact parameter in UPCs

Excitation of the nuclei possible through secondary photon exchange

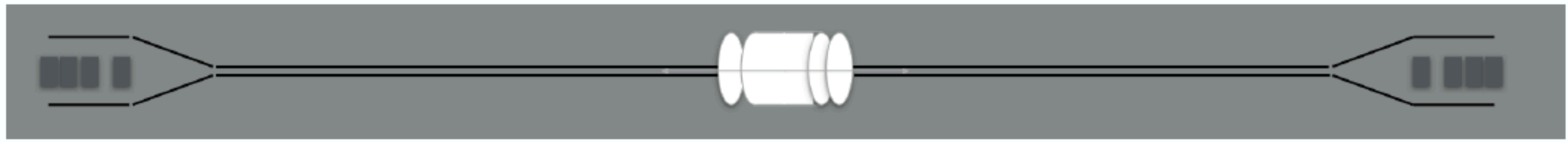
"Giant dipole resonance"
All protons vibrating against all neutrons
→ Knocks out 1-4 neutrons



Can be "count" in zero degree calorimeters



Zero degree calorimeters (ZDC) z=±140m: neutrons & photons $|\eta|>8.3$



Varying impact parameter in UPCs

S. Klein, P. Steinberg,
Annu. Rev. Nucl. Part. Sci. 70(1), 323 (2020)

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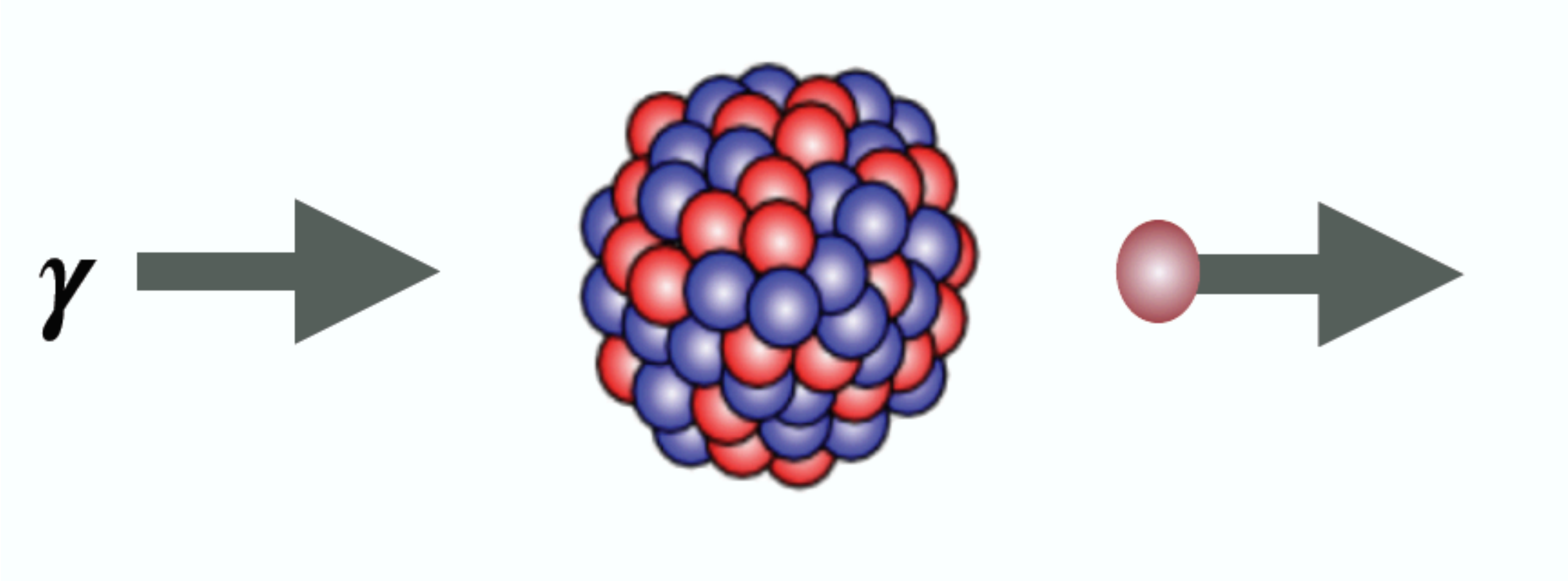
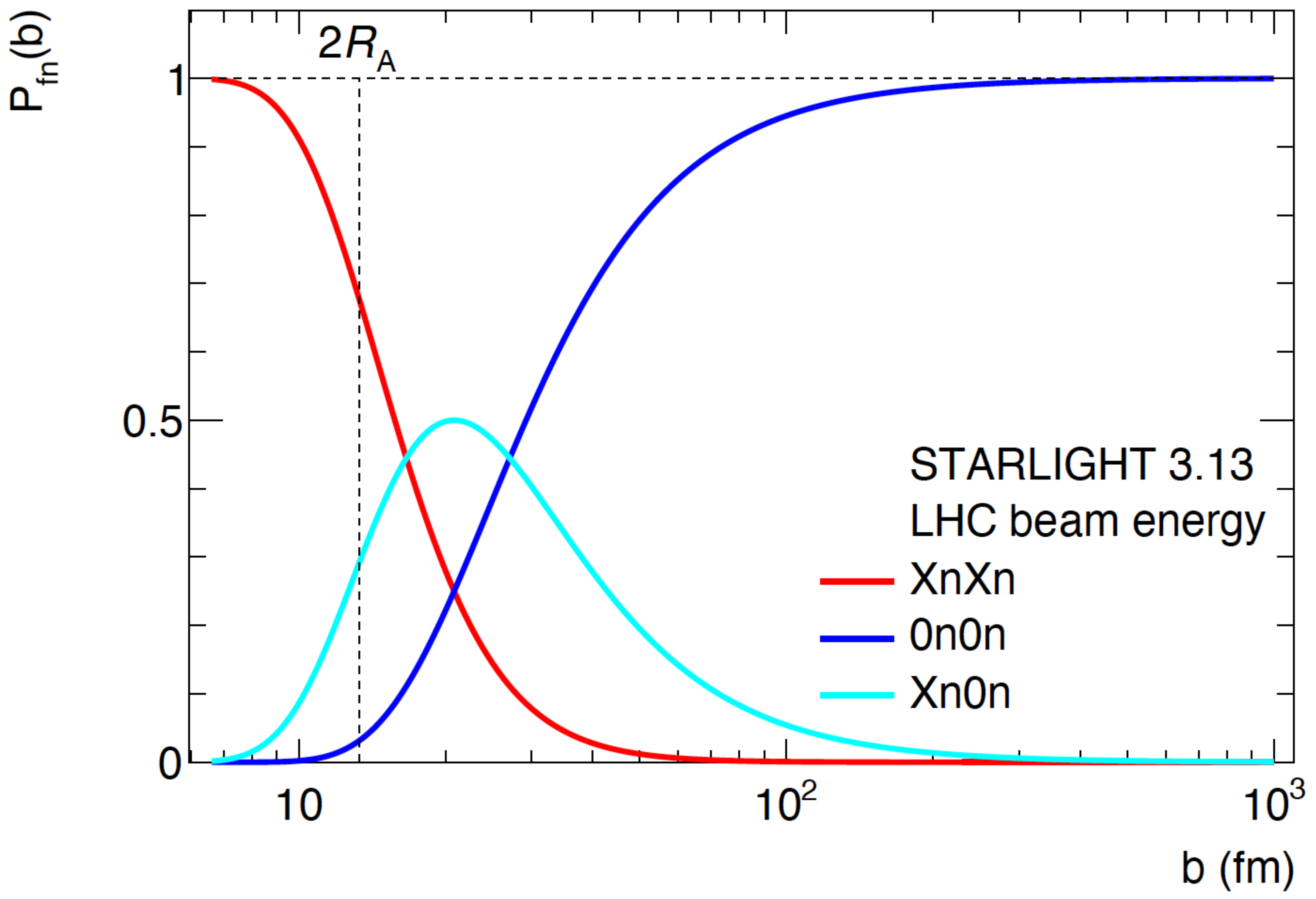


Can be "count" in zero degree calorimeters



Classify UPC events according to
0n0n, Xn0n/0nXn or XnXn
→ Selection select also a impact parameter range
→ Probe impact parameter dependences

Varying impact parameter in UPCs

ATLAS, Phys. Rev. C 104 (2021) 024906

$p_{T,\mu} > 4$ GeV, $|\eta_\mu| < 2.4$, $m_{\mu\mu} > 10$ GeV, $p_{T,\mu\mu} < 2$ GeV/c

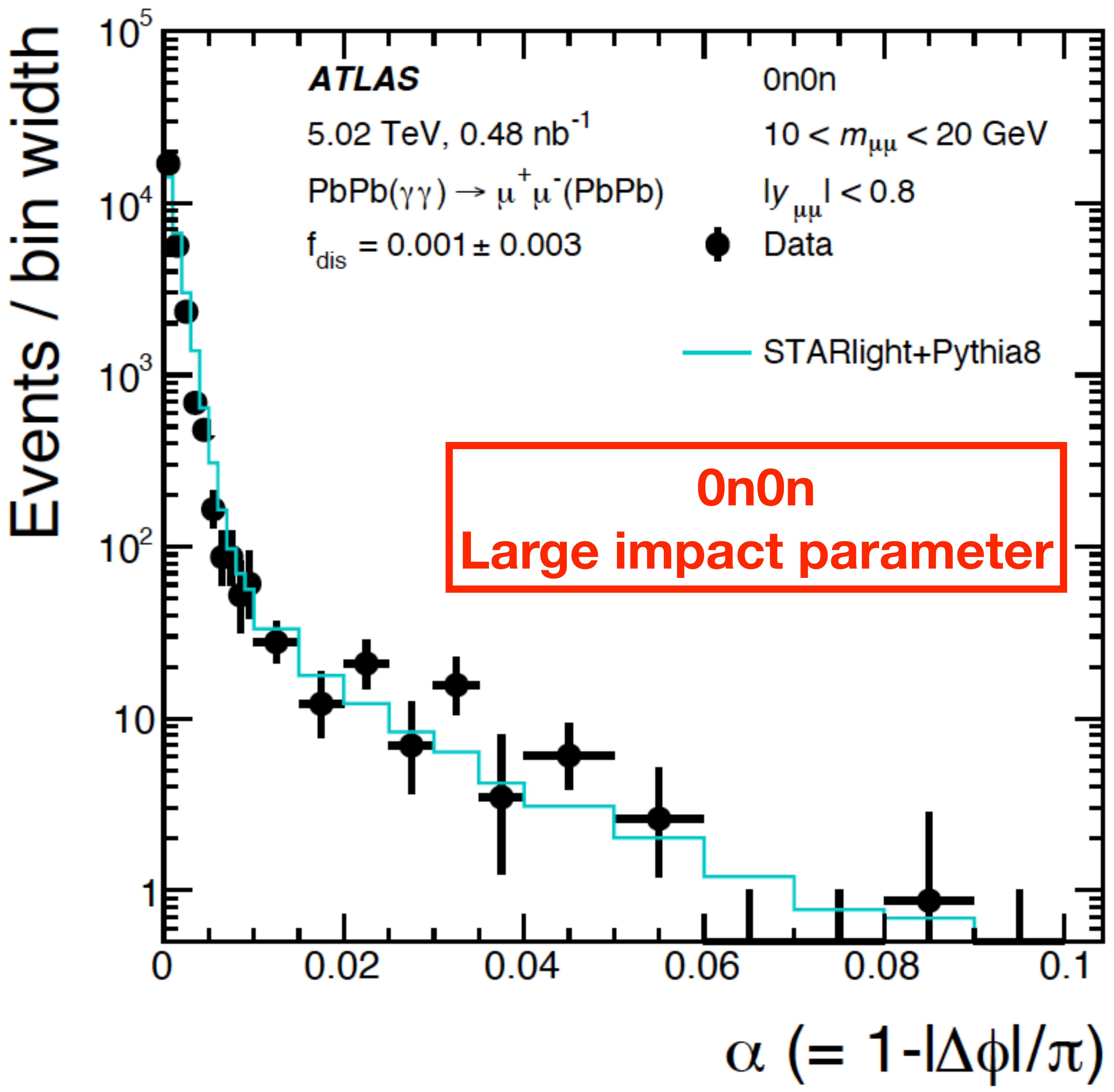
Measure acoplanarity of $\mu^+\mu^-$ pairs:

$$\alpha_{\mu^+\mu^-} = 1 - \frac{\Delta\varphi_{\mu\mu}}{\pi}$$

Low p_T of quasi real photons

→ Low dimuon $p_{T,\mu\mu}$ (back-to-back)

→ $\alpha_{\mu\mu} << 1$



Varying impact parameter in UPCs

ATLAS, Phys. Rev. C 104 (2021) 024906

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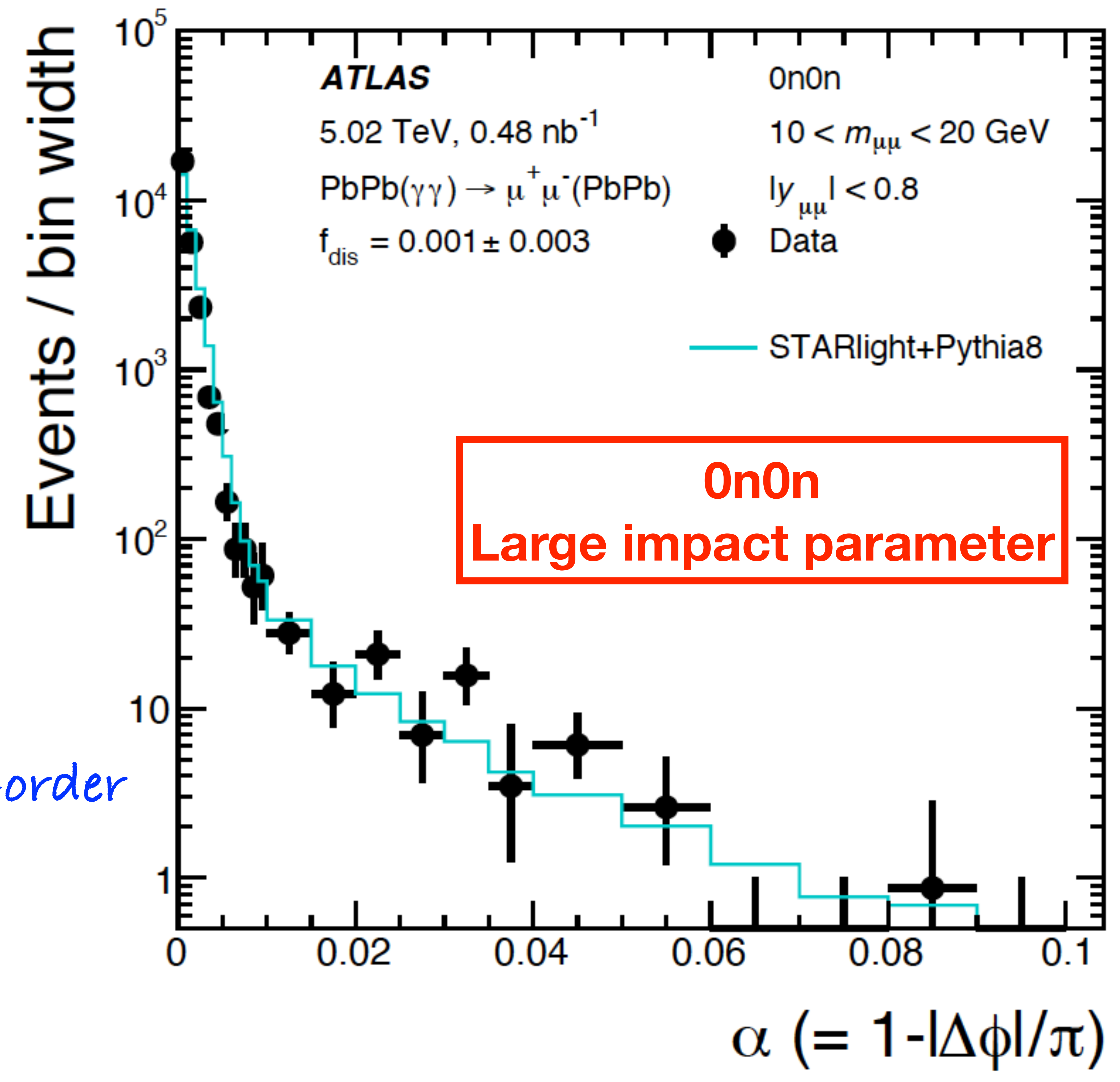
0n0n Large impact parameter:

Tail for $\alpha_{\mu^+\mu^-} > 0.01$: higher order process relevant
Here final-state radiation using Pythia8

$p_{T,\mu} > 4$ GeV, $|\eta_\mu| < 2.4$, $m_{\mu\mu} > 10$ GeV, $p_{T,\mu\mu} < 2$ GeV/c



Current QED calculations (& EPA, Wigner) at leading-order
Higher-order contributions not yet 100% clear

G.Baur, Eur. Phys. J. D 55 (2009) 265
W. Zha and Z. Tang, arXiv:2103.04605

Varying impact parameter in UPCs

ATLAS, Phys. Rev. C 104 (2021) 024906

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Measure acoplanarity of $\mu^+\mu^-$ pairs:

$$\alpha_{\mu^+\mu^-} = 1 - \frac{\Delta\varphi_{\mu\mu}}{\pi}$$

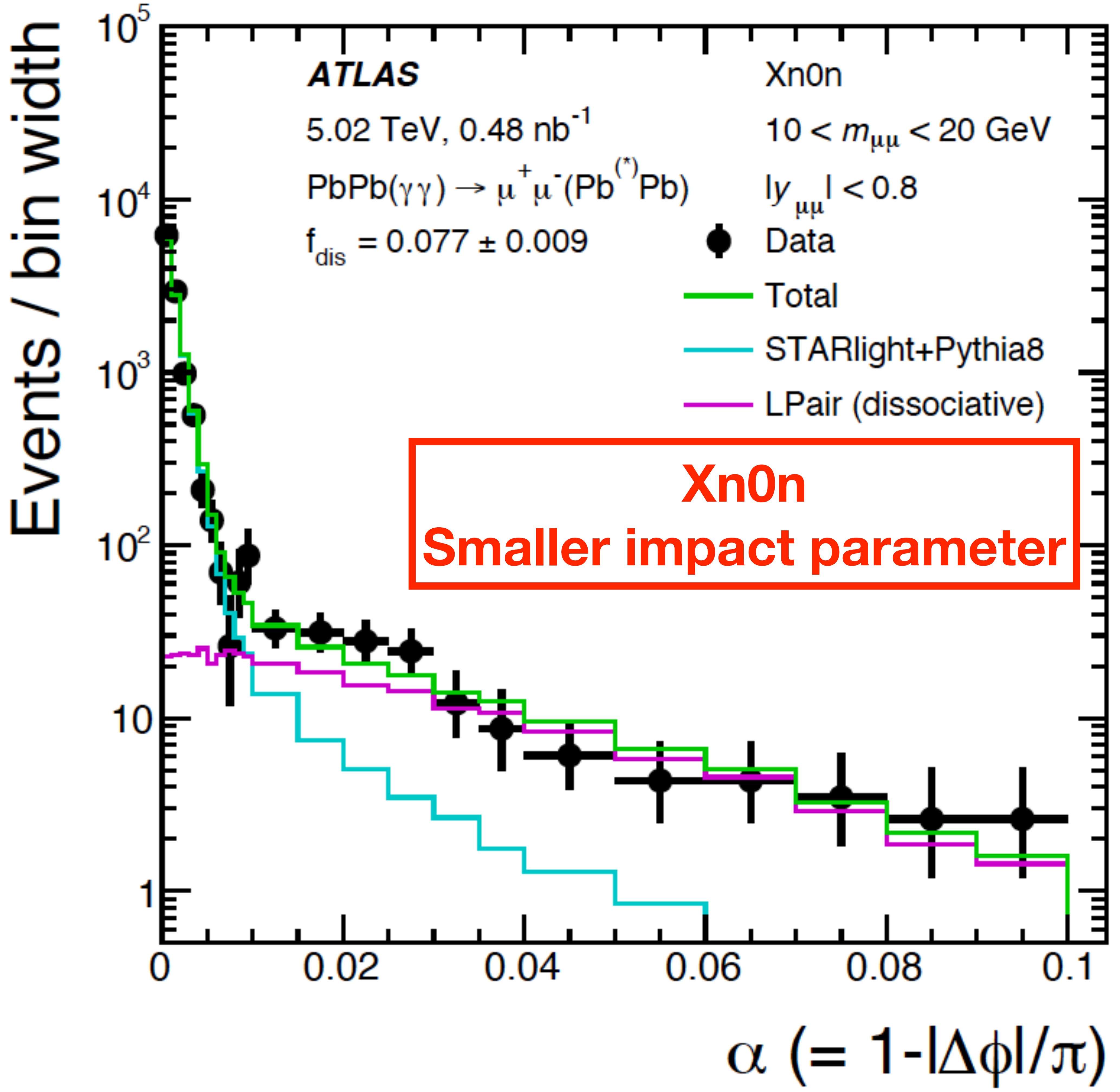
Xn0n: smaller impact parameter:

Larger tails for $\alpha_{\mu^+\mu^-} > 0.01$

ATLAS: template fit

- Including incoherent dissociative process with γ emitted by substructure of one of the nucleons
- **Assuming b independent** $\alpha_{\mu^+\mu^-}$ shape for coherent $\gamma\gamma \to \mu^+\mu^-$

$\to \alpha_{\mu^+\mu^-}$ **distributions well described**



Varying impact parameter in UPCs

CMS, Phys. Rev. Lett 127 (2021) 122001

Measure acoplanarity of $\mu^+\mu^-$ pairs:

$$\alpha_{\mu^+\mu^-} = 1 - \frac{\Delta\varphi_{\mu\mu}}{\pi}$$

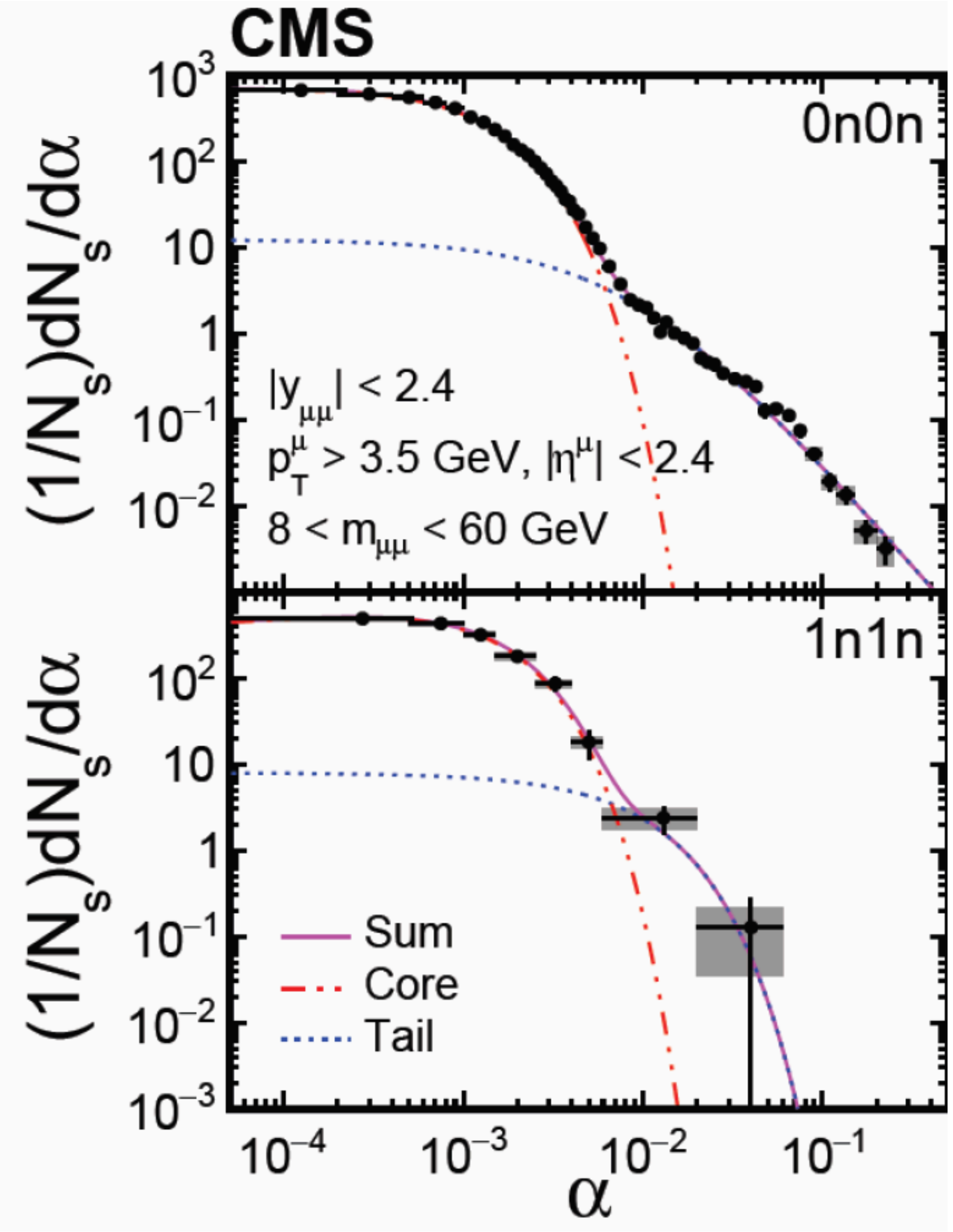
Xn0n: smaller impact parameter:

Larger tails for $\alpha_{\mu^+\mu^-} > 0.01$

Other approach by CMS:

- Two function fit:
  - Core: leading order
  - Tail: soft γ

→ **Observed broadening of the core** qualitative **described by LO-QED calculations** for coherent $\gamma\gamma \to \mu^+\mu^-$ **including *b* dependence** of the p_T distribution of the initial γ



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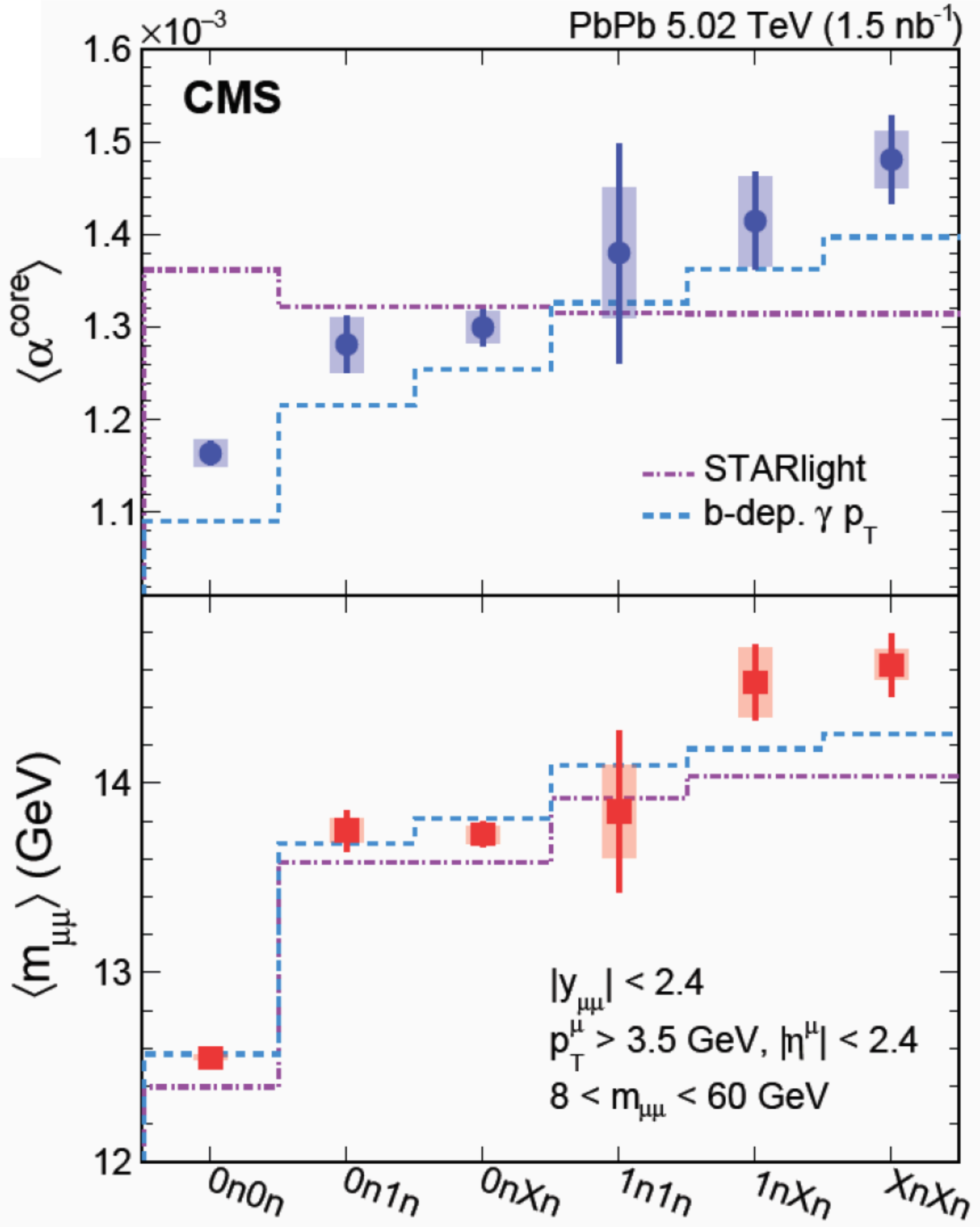

Varying impact parameter in UPCs

CMS, Phys. Rev. Lett 127 (2021) 122001

Measure acoplanarity of $\mu^+\mu^-$ pairs:

$\alpha_{\mu^+\mu}$ ...

Xn0n: smaller i...

Larger tails for ...

Other approac...

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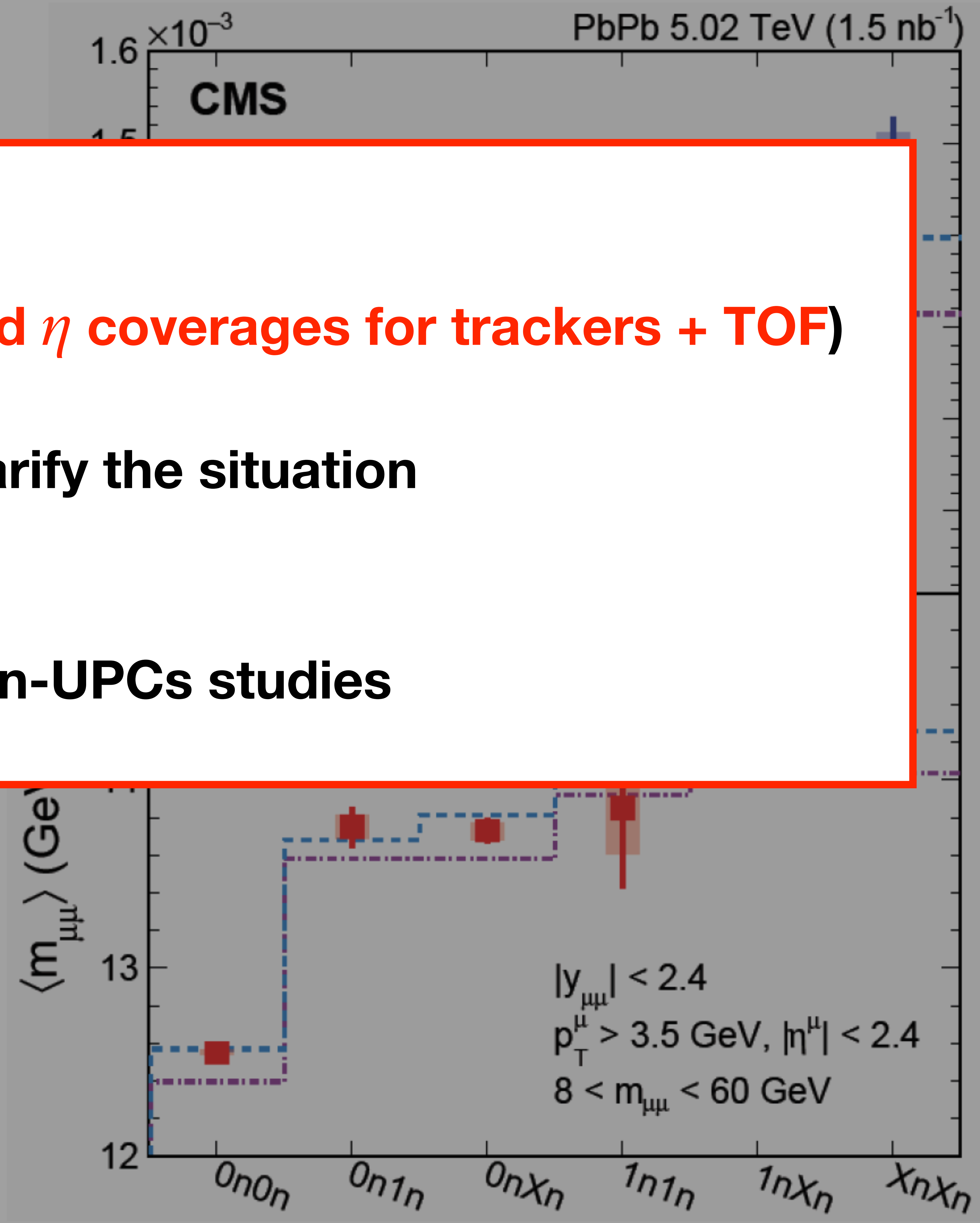


Runs 3 + 4:

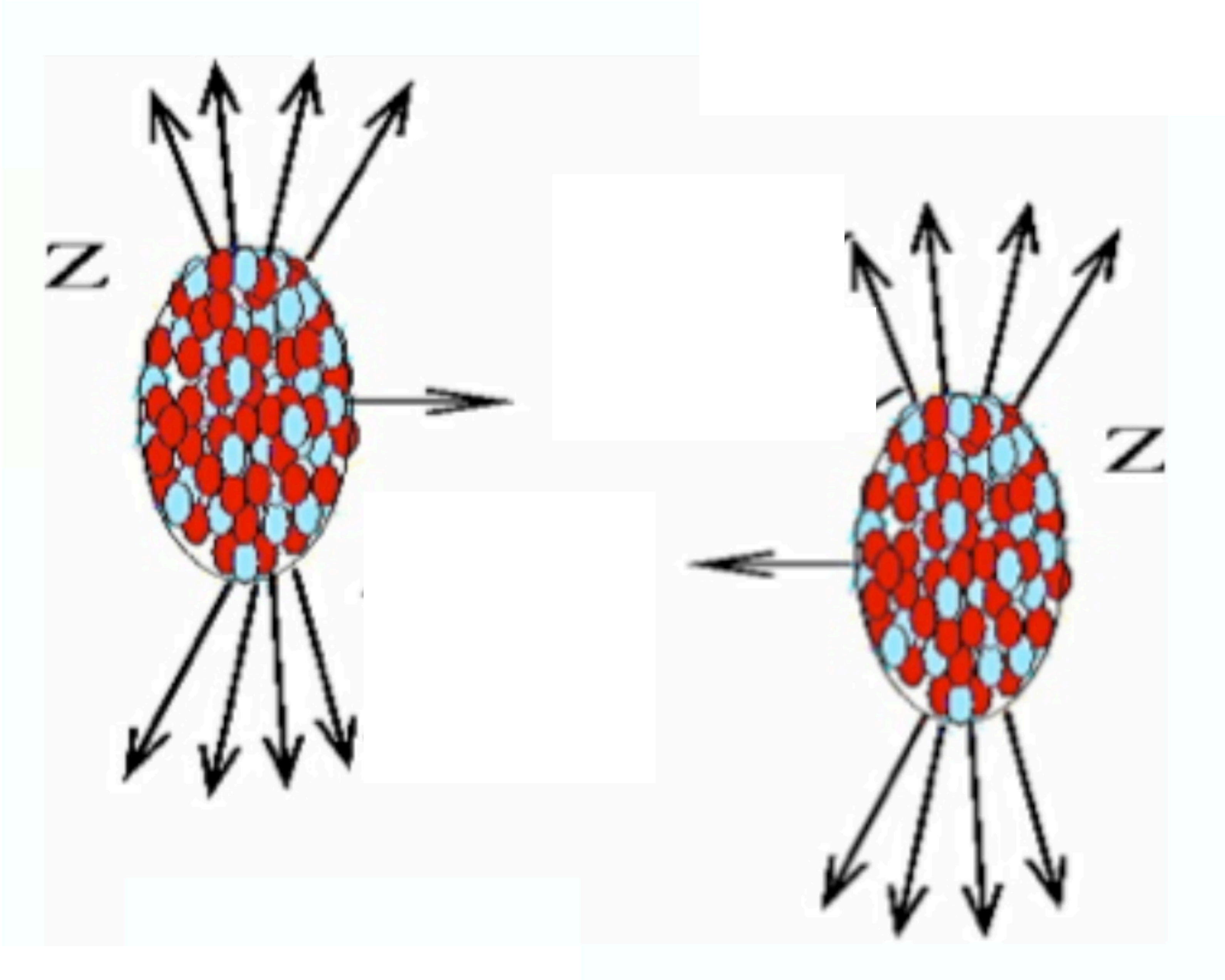
Upgrades of the detectors (trigger, ZDCs, extended η coverages for trackers + TOF)
Significant increase in statistics

→ More precise (and differential) results to clarify the situation

→ Further theory development also needed !

Goal: calibrate the photon flux also relevant for non-UPCs studies

$\gamma\gamma \rightarrow l^+l^-$ in collisions with hadronic interactions



Impact parameter $b < R_1 + R_2$

Current measurements:

- **At RHIC: STAR in peripheral collisions**
  $0.4 < m_{ee} < 2.6$ GeV/c^2
  STAR, Phys. Rev. Lett. 121 (2008) 132301
- **At the LHC:**
  - **ATLAS towards central Pb—Pb collisions**
    $8 < m_{\mu\mu} < 45$ GeV/c^2 and $p_{T,\mu} > 4$ GeV/c
    ATLAS, Phys. Rev. Lett. 121 (2018) 212301
    ATLAS, arXiv: 2206.12594
  - **ALICE in peripheral Pb—Pb collisions**
    $0.4 < m_{ee} < 2.6$ GeV/c^2
    ALICE, arXiv:2204.11732

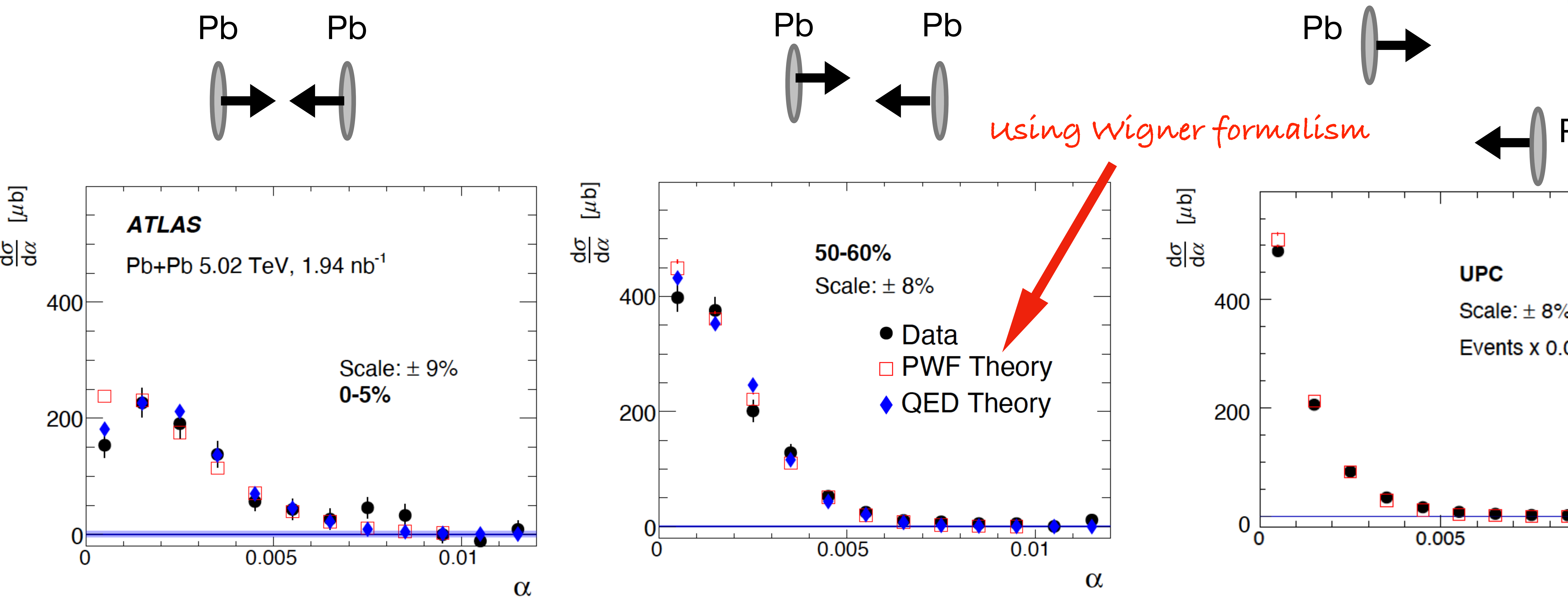
$\gamma\gamma \rightarrow l^+l^-$ in collisions with hadronic interactions

ATLAS, arXiv: 2206.12594

Observe a broadening of pair p_T & α going from UPC to central Pb—Pb collisions

$\gamma\gamma \rightarrow l^+l^-$ in collisions with hadronic interactions

ATLAS, arXiv: 2206.12594



Observe a broadening of pair p_T & α going from UPC to central Pb—Pb collisions

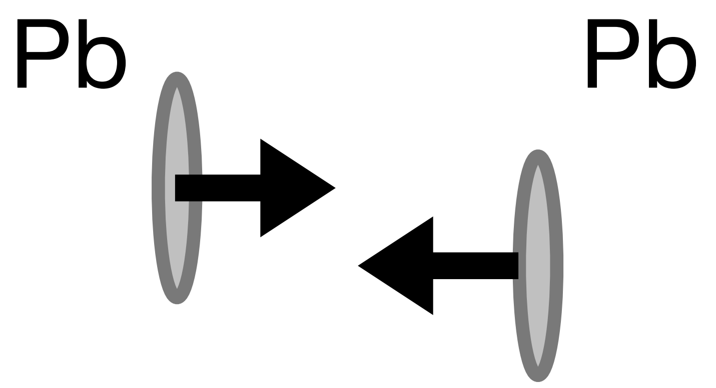
Calculations:

First idea (2018): broadening coming from hot-medium effects

Later: including b dependence of the initial photon p_T improved significantly the description of the data

Hunt for medium effects

S. Klein, A. H. Mueller, B.-W.Xiao, and F.Yuan, Phys. Rev. Lett. 122 (2019) 132301
ATLAS, arXiv:2206.12594

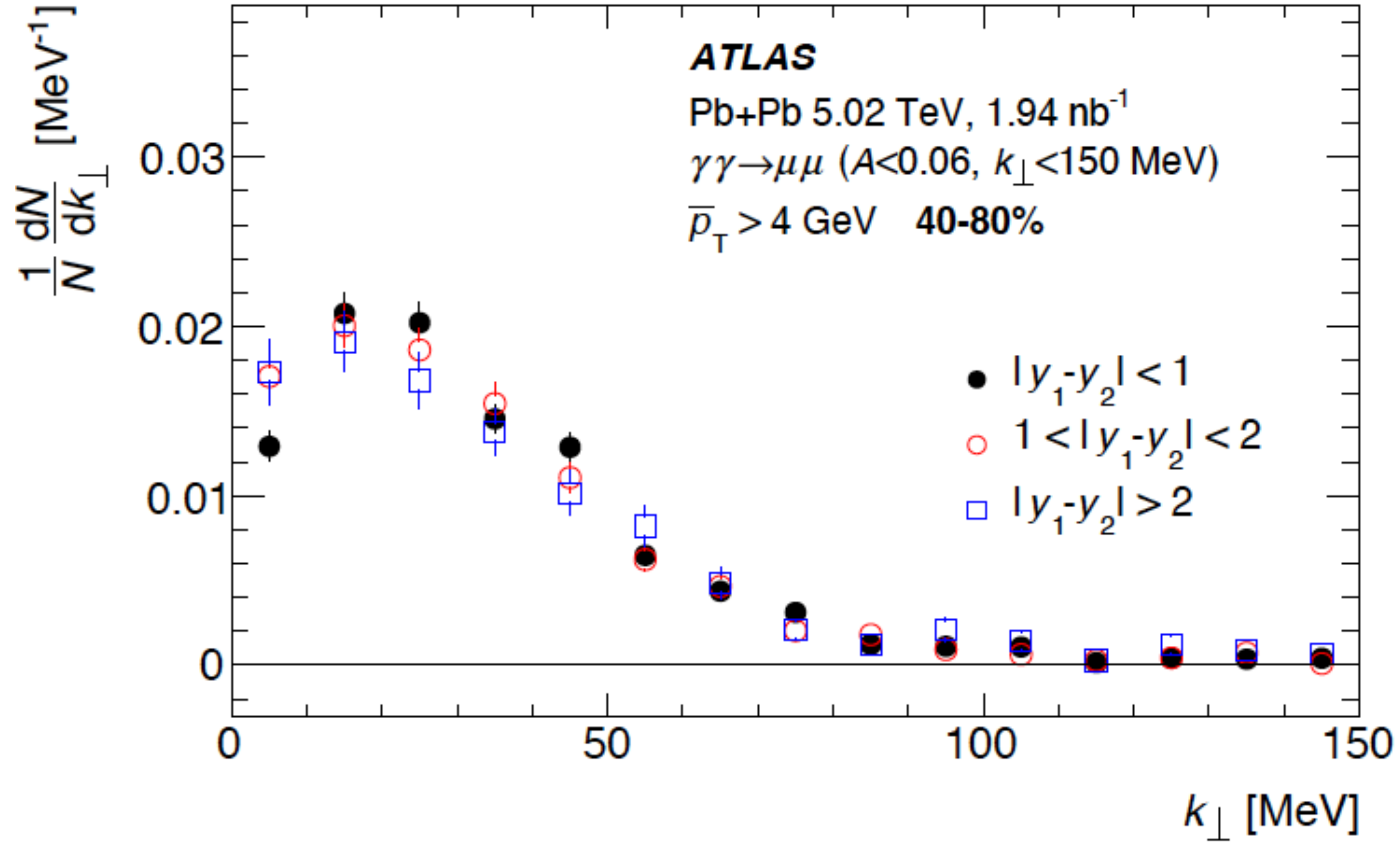


Deflection of the μ in magnetic fields generated during the Pb—Pb collision

- Expect a dependence of the broadening
  Increasing as a function of $|\Delta_y| = |y_{\mu_1} - y_{\mu_2}|$
- Expect a dependence of the l^+l^- yield with $|2(\varphi_{ll} - \Psi_2)|$
  φ_{ll} azimuthal orientation of the dilepton
  Ψ_2 second-order event plane angle

No sign of such effects at the moment from ATLAS data

Expect precision measurements
from Runs 3 + 4 and beyond



$$k_\perp \equiv \frac{1}{2}(p_{T1} + p_{T2})\,(\pi - |\phi_1 - \phi_2|) = \pi\alpha\bar{p}_T$$

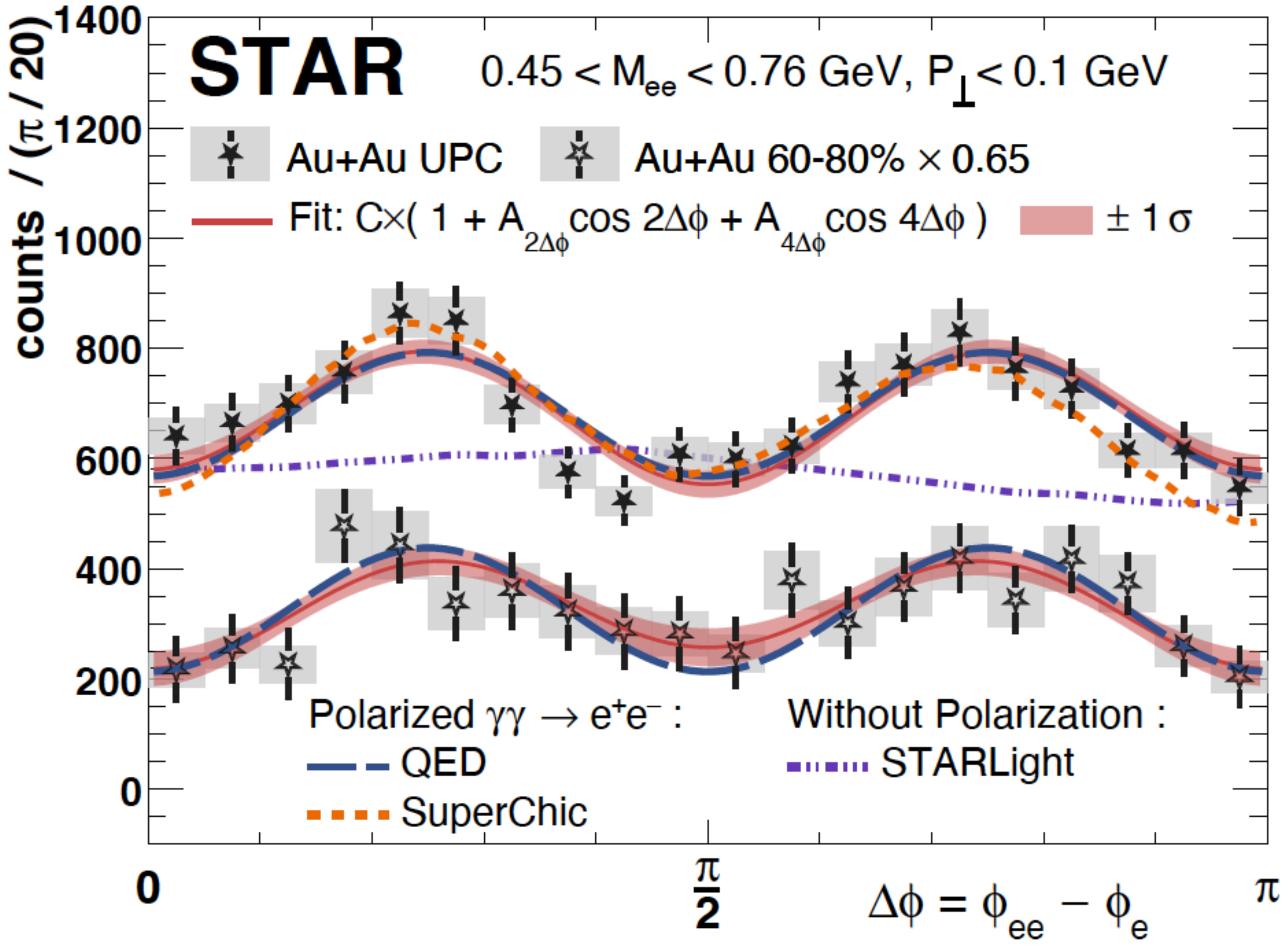
Some further future prospects

STAR, Phys. Rev. Lett. 127 (2021) 052302

Probe the initial photon polarisation
(Not yet measured at the LHC)

$\cos(4\Delta\phi)$ modulation as signature of Breit-Wheeler process
(due to the initial linear γ polarisation)
$\Delta\phi$ = azimuthal angle between pair $p_{\mathrm{T,ll}}$ and $p_{\mathrm{T,l}}$

→ Final state interactions could wash-out this modulations



ALICE measures dielectrons
In the same kinematic range as STAR
But for γ_L 30 larger

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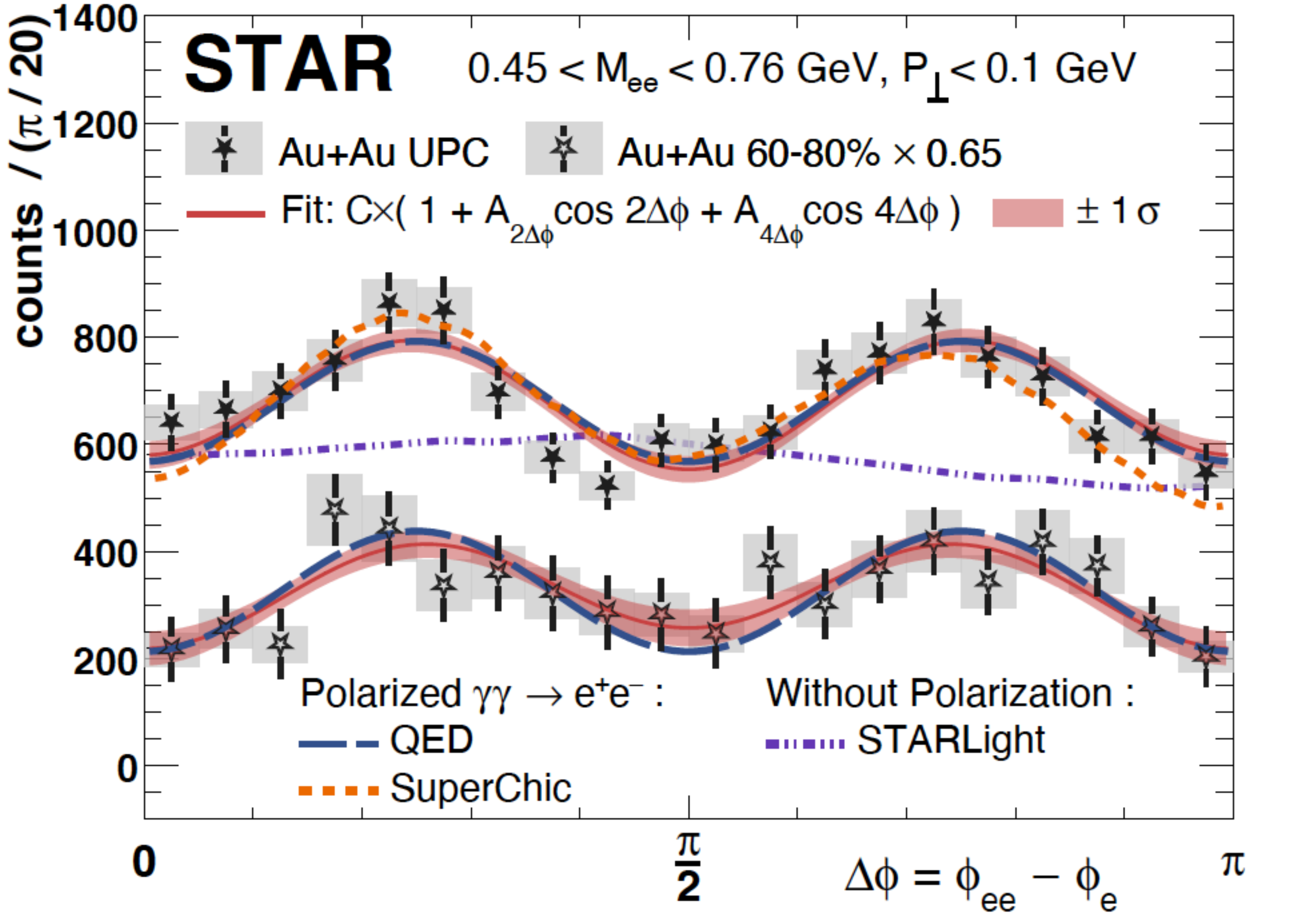


ALICE measures dielectrons
In the same kinematic range as STAR
But for γ_L 30 larger

Runs 3+4 and beyond:
Precise differential measurements for $\mu^+\mu^-$ & e^+e^- over extended $m_{l^+l^-}$ and centrality ranges

- Test QED calculations
- Map the electromagnetic fields
- Search further for possible medium effects
  (May be larger for e^+e^- due to smaller m)

Focus 3: dark photons

Dark photons

PAMELA, Nature 458 (2009) 607
FERMI, Phys. Rev. Lett. 108 (2012) 011103
AMS, Phys. Rev. Lett. 110 (2013) 141102
Muon g-2, Phys. Rev. D73 (2006) 072003

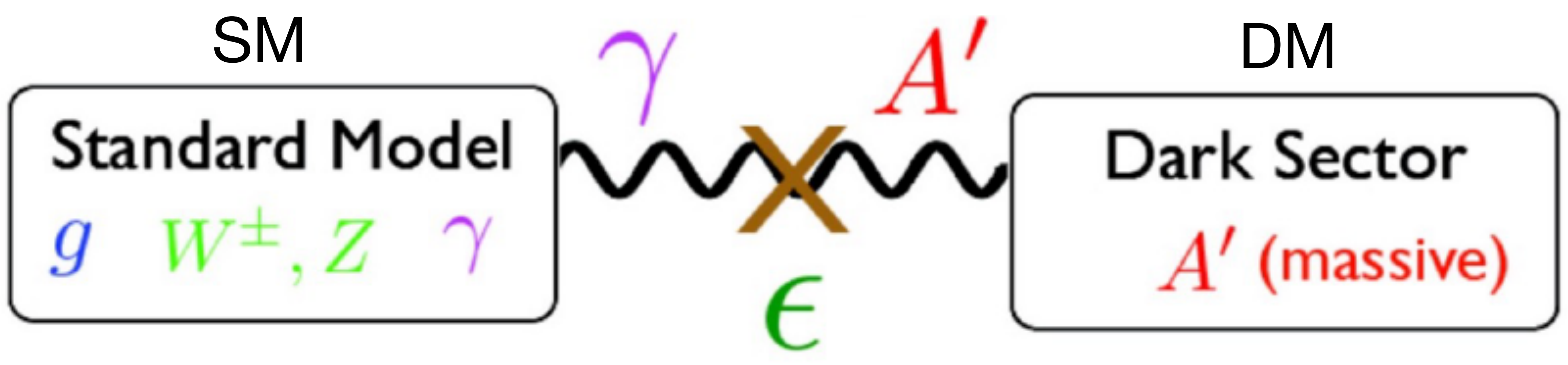
- Dark matter: $\approx$ 80% of the matter in the Universe
- Possible candidates (among others): dark photon A'
- Hypothetical extra-U(I) gauge bosons, motivated by:
    - Antiproton spectrum in the cosmic rays measured by AMS Collaboration
    - Positron excess in the cosmic rays observed by PAMELA and confirmed by FERMI & AMS
    - Muon anomalous magnetic moment

$$L = L_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'_{\mu}A'^{\mu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

Standard Model Lagrangian

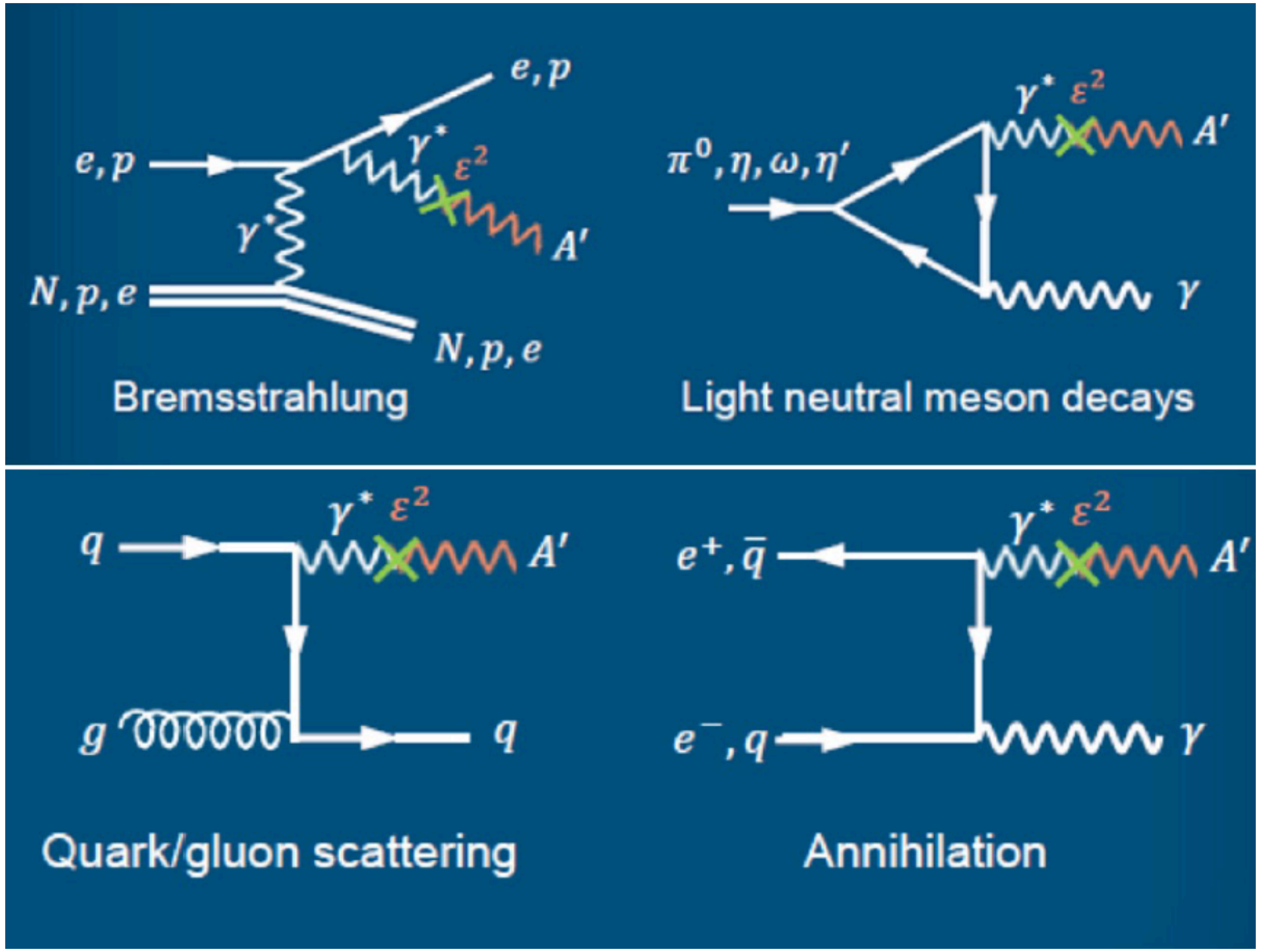
Additional U(1) symmetry describing the new force carried by a massive vector boson, ***the Dark photon A'***

Kinetic mixing term with the ***standard photon γ***



Messenger particle of a dark sector with **residual interactions** ϵ to the SM sector and **mass** $m_{A'}$

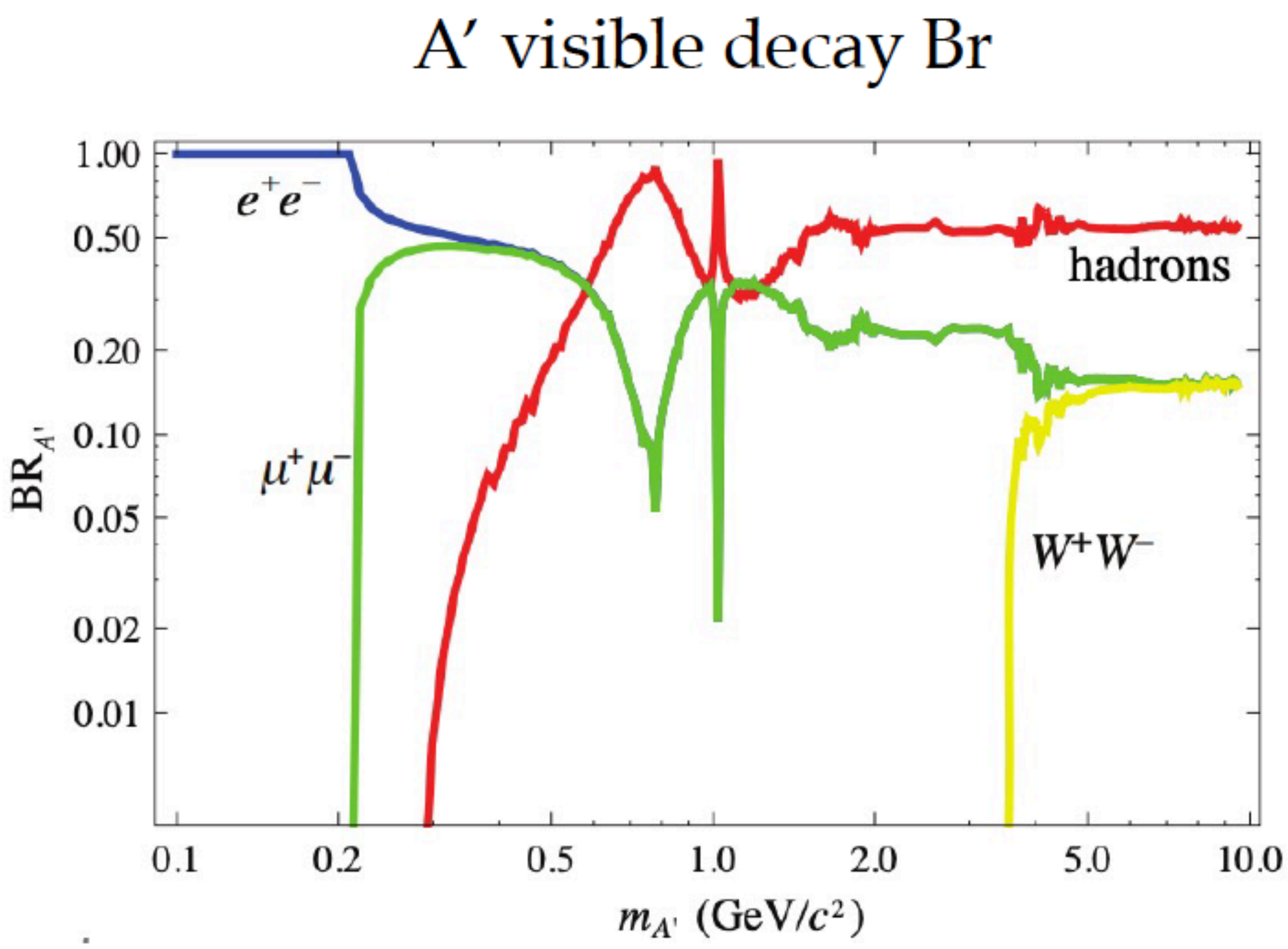
Dark photon production



R. Jacobsoon (CERN), LHC Operations Workshop, Evian (2019)

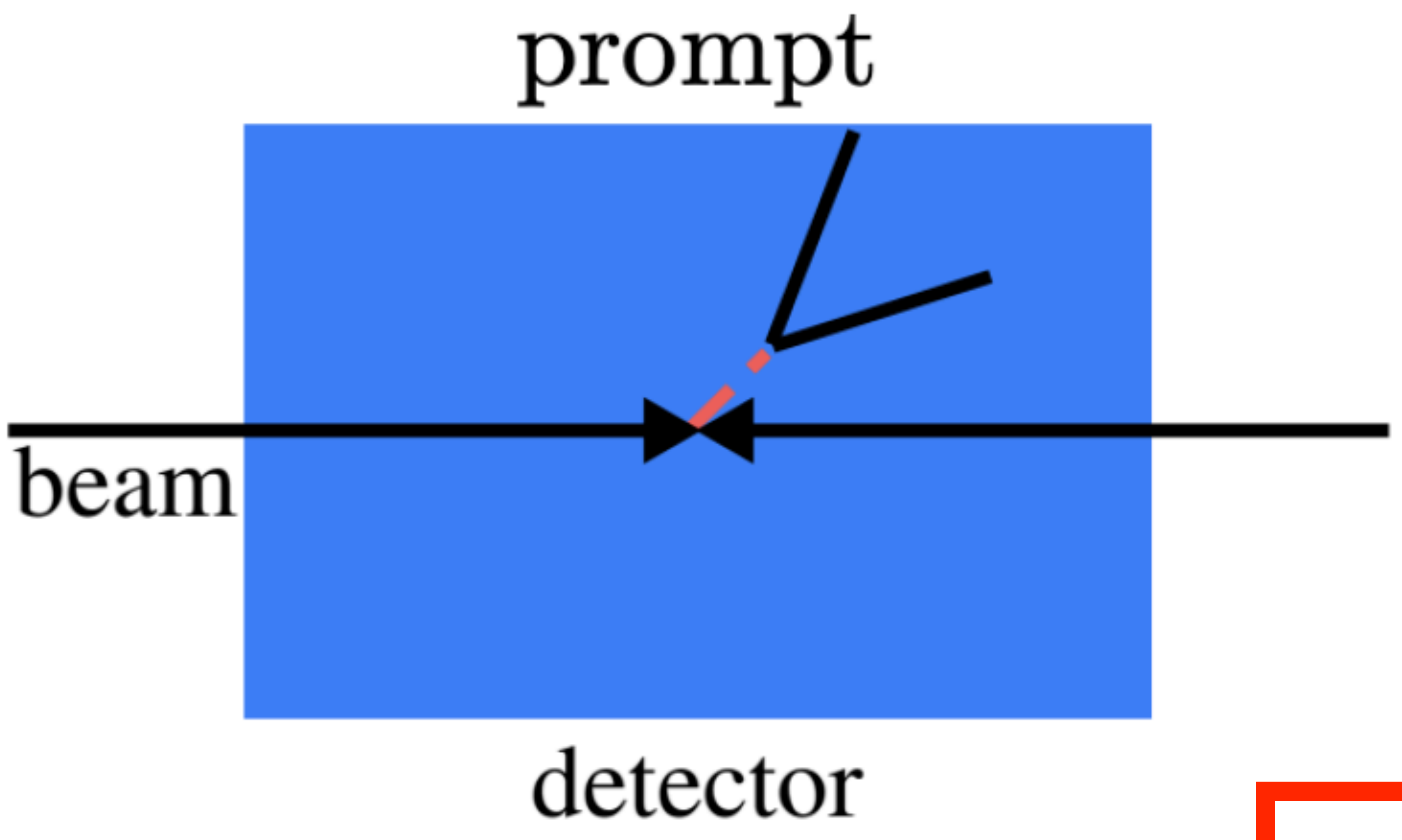
Dark photon decays

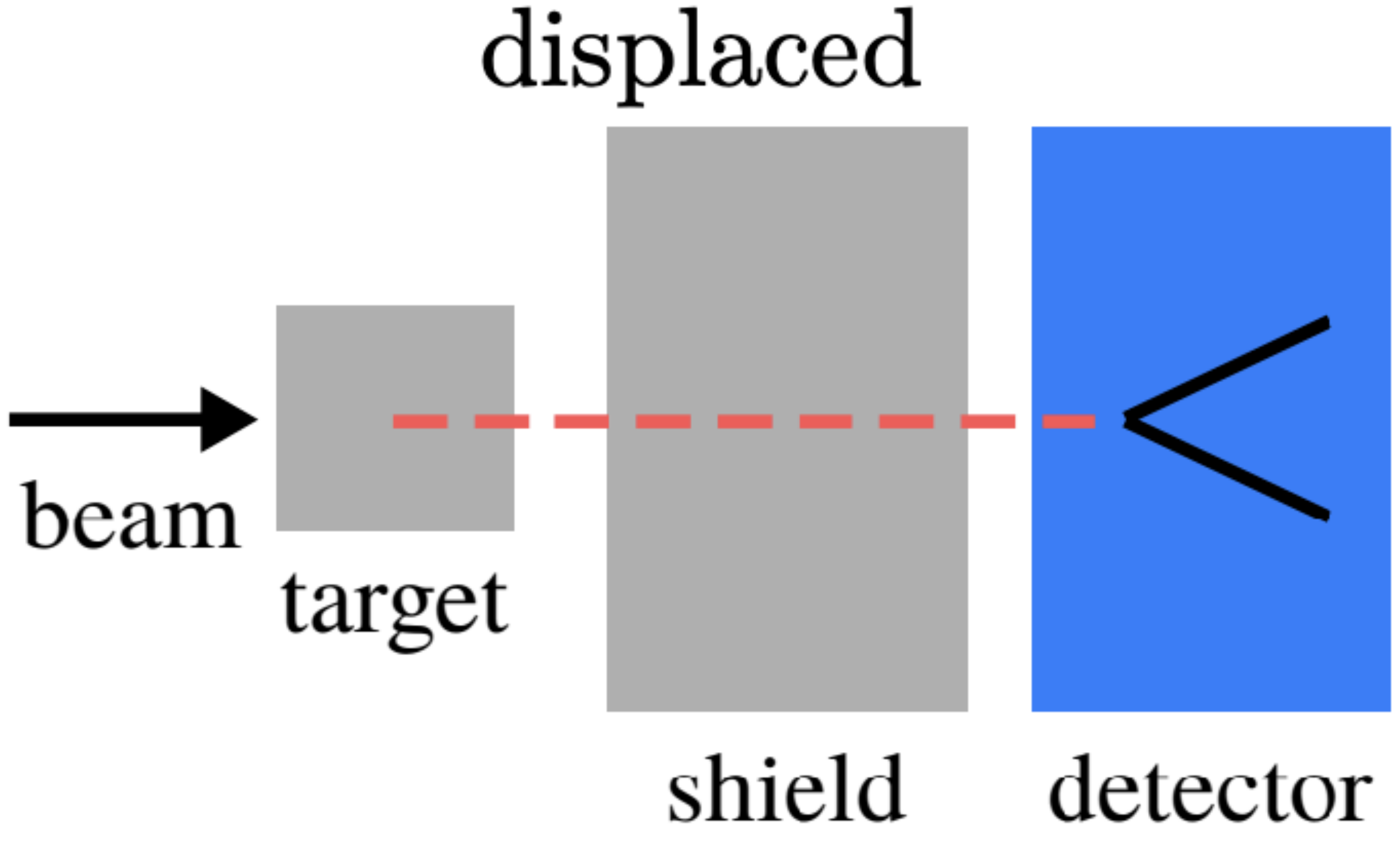
- Visible decays (No DM with $m_{\mathrm{DM}} < m_{\mathrm{A'}}/2$)
  - $A' \rightarrow$ SM particle
- Invisible decays (DM with $m_{\mathrm{DM}} < m_{\mathrm{A'}}/2$ exists)
  - $A' \rightarrow$ DM with BR≈1
    - SM decays suppressed by a factor ϵ^2



Gabriele Piperno, PANIC (2017)

Dark photon searches





$$\tau(\mathrm{A}') \propto [m(\mathrm{A}')\epsilon^2]^{-1}$$

Prompt:

- Sensitive to shorter lifetimes
- Search for a bump on a large background

Displaced:

- Sensitive to longer lifetimes (smaller ϵ and $m_{\mathrm{A}'}$)
- Smaller background

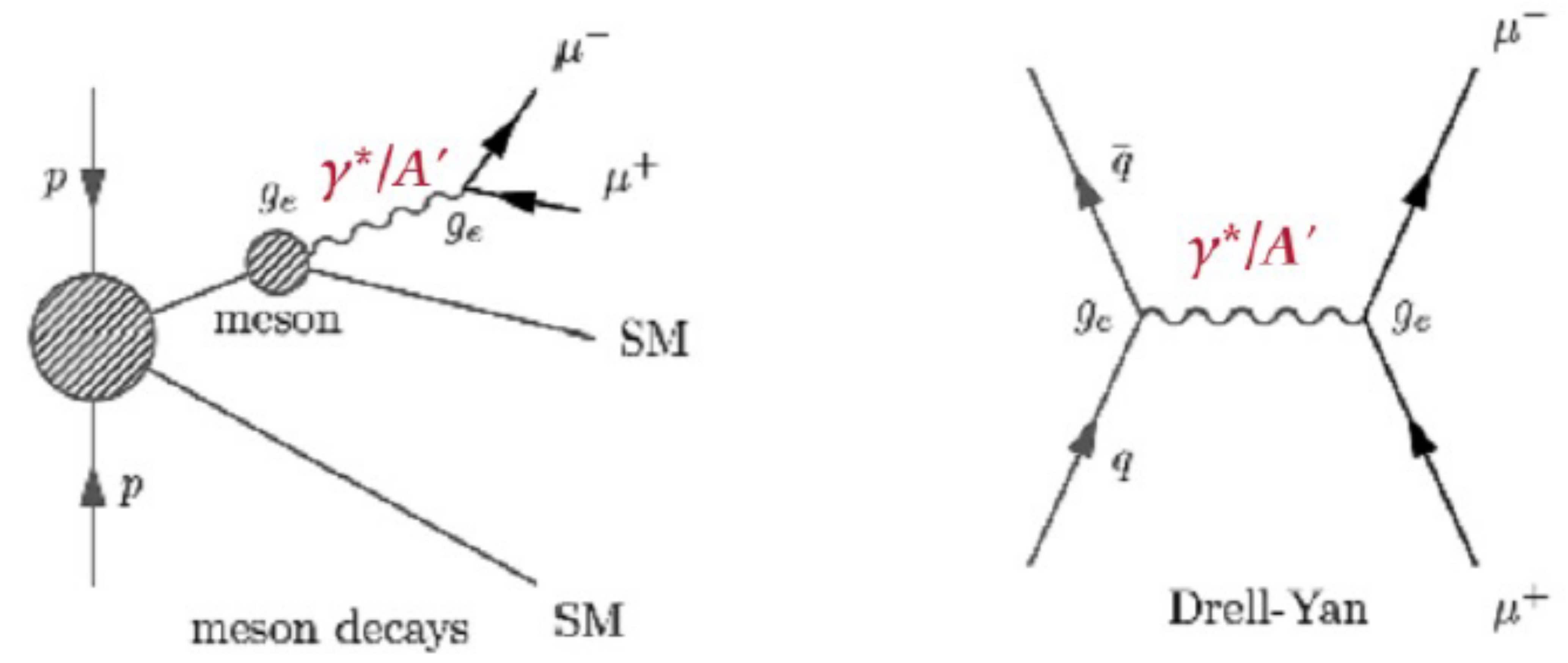
Many experiments, here focus on LHC experiments

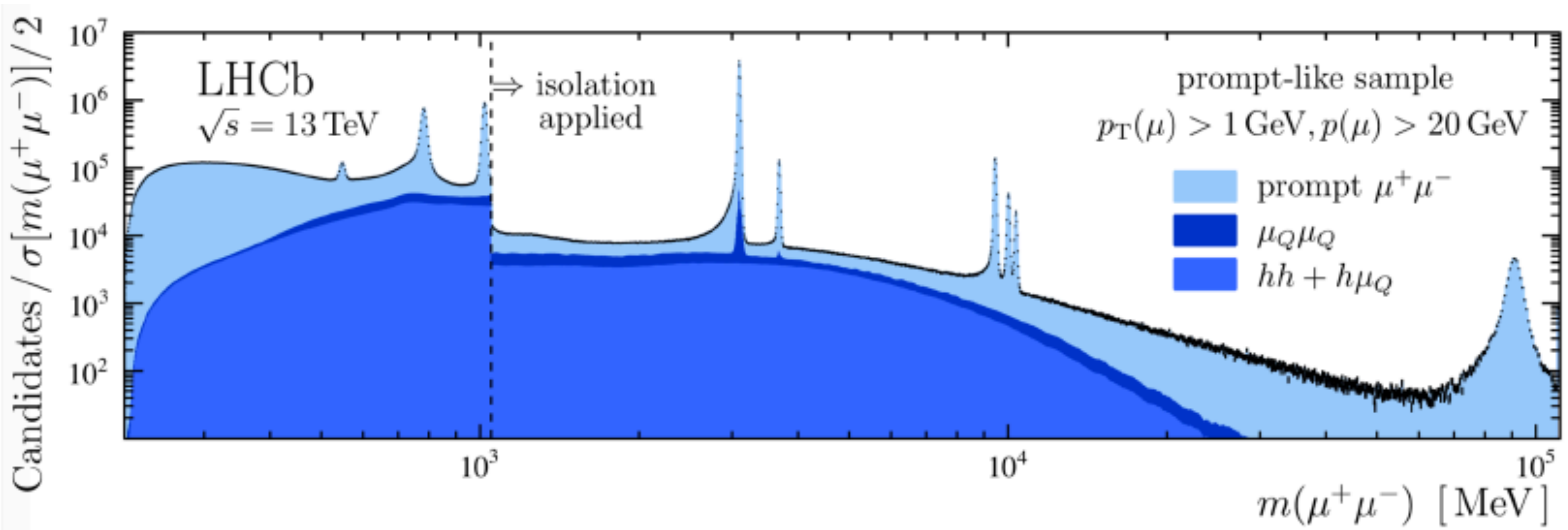
Current limits from LHC

LHCb, Phys. Rev. Lett. 120 (2018) 061801
CMS, Phys. Rev. Lett. 124 (2020) 131802
ALICE Preliminary

- $A' \rightarrow \mu^+\mu^-$ **in pp collisions at** $\sqrt{s} = 13$ **TeV**
  - Prompt searches
    - Meson decays: $m_{A'} < 1$ GeV
    - Drell-Yan: $m_{A'} > 1$ Ge
  - Displaced searches (0.1-1cm) for long lived A'
    - Background dominated by material interactions
    - Precise knowledge of location of material needed
  - Inclusive searches with $m_{A'}$ in 30-75 and 110-200 GeV ranges
- $A' \rightarrow e^+e^-$ **in pp and p—Pb collisions**
  - Inclusive searches with $0.02 < m_{A'} < 0.1$ GeV

Prompt searches





Current limits from LHC

- $A' \rightarrow \mu^+\mu^-$ **in pp collisions at** $\sqrt{s} = 13$ **TeV**
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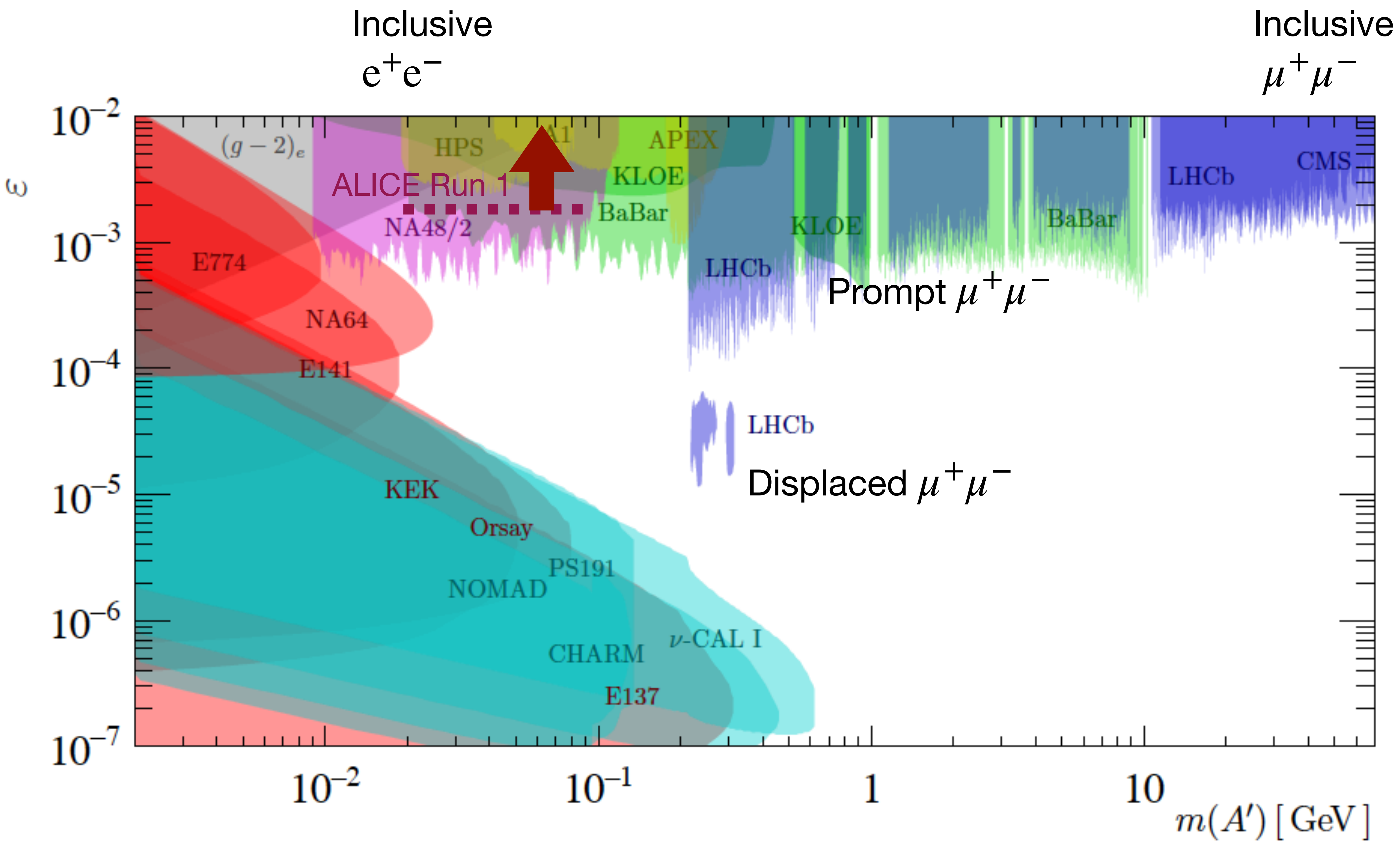
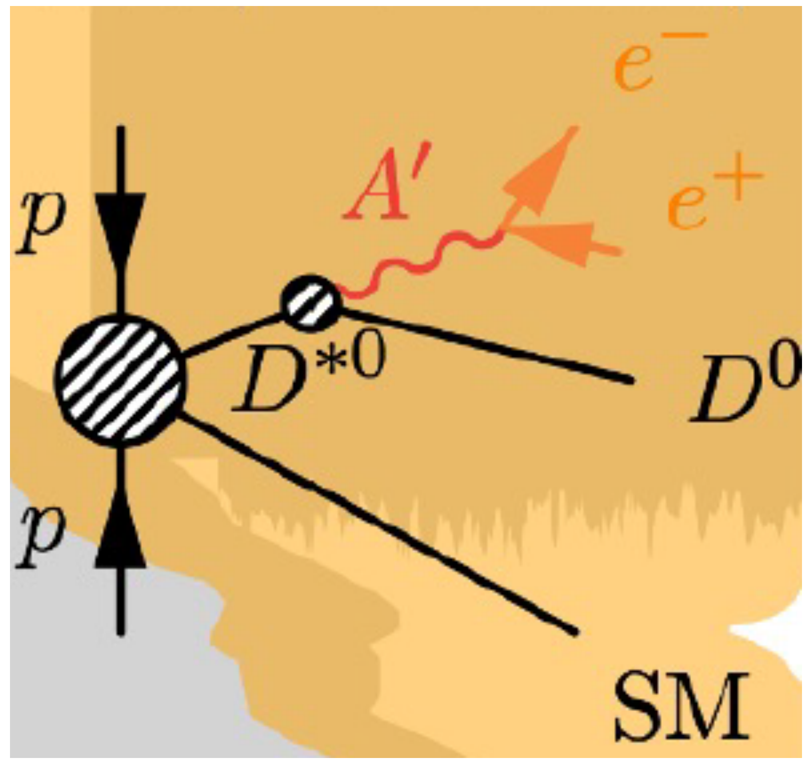


M. Graham, C. Hearty, M. Williams, arXiv:2104.10280

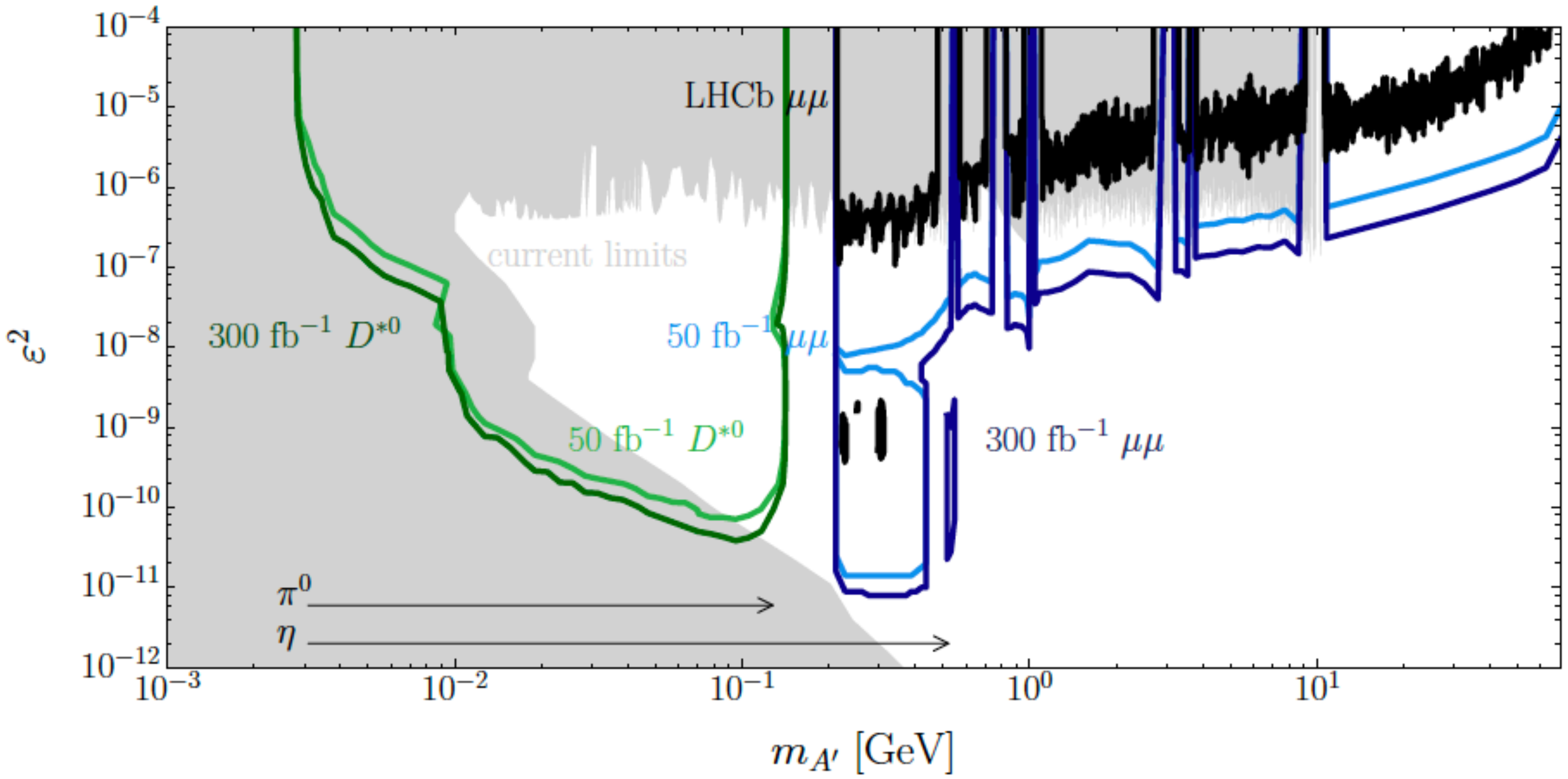
Future prospects

Search in $D^{*0} \to A'D^0, A' \to e^+e^-$



Add new constraints below $m_{A'}$ of 125 MeV

A. Dainese *et al.*, CERN-2019-007



Will profit from upgrades of the vertex detector and removing of LHCb hardware trigger (for Run > 3)

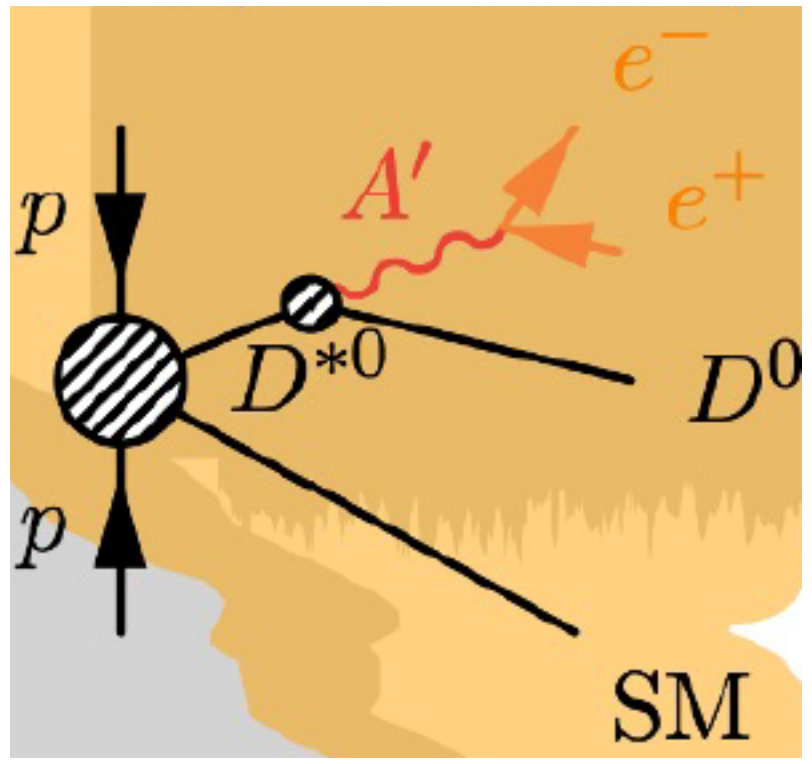
Black existing limits

Projections for pp collisions:

- Run 3 + 4: 50 fb^{-1}
- Run 5: 300 fb^{-1}

Future prospects

Search in $D^{*0} \rightarrow A'D^0, A' \rightarrow e^+e^-$



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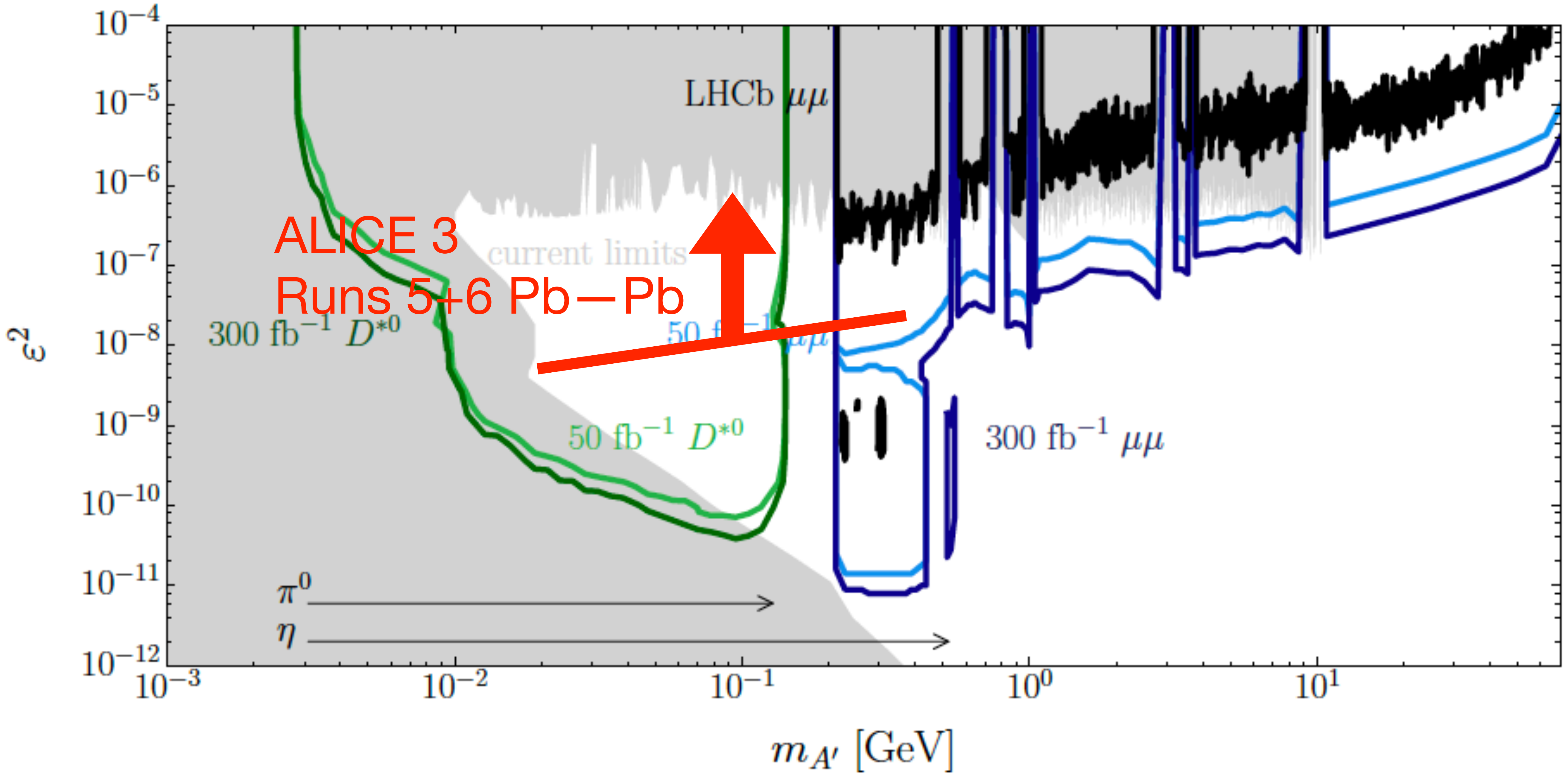

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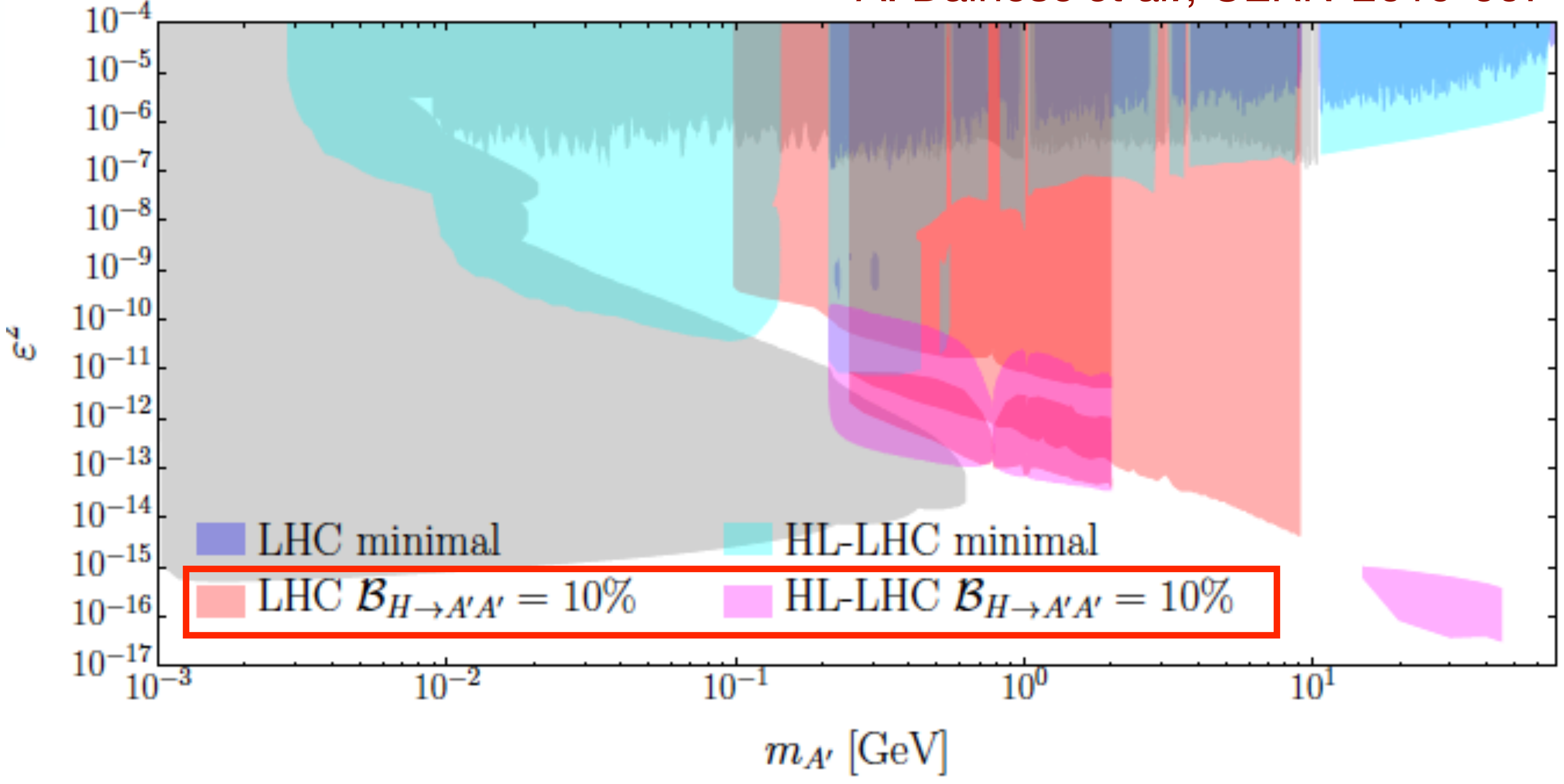
Black existing limits

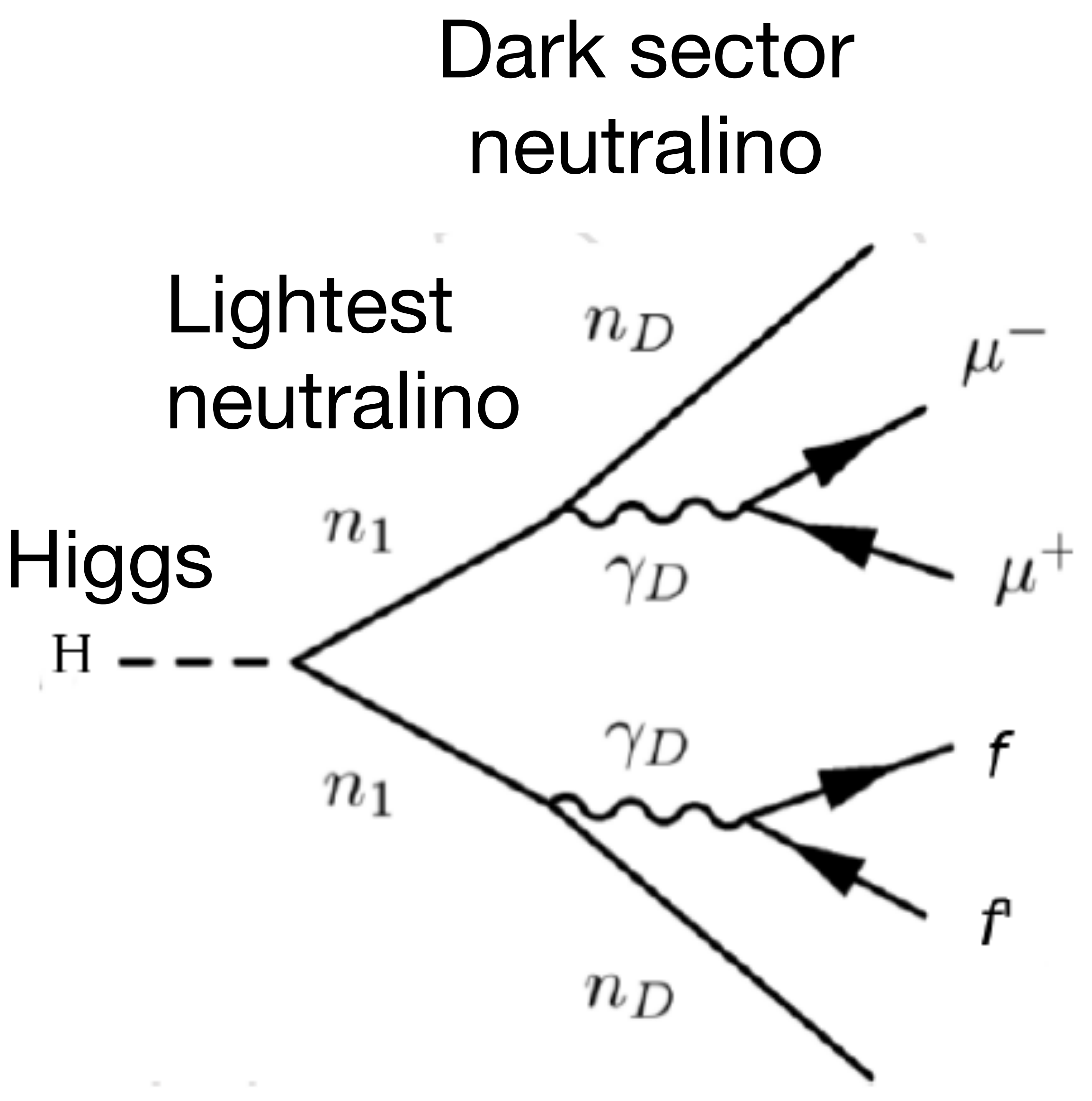
Projections for pp collisions:

- Run 3 + 4: 50 fb^{-1}
- Run 5: 300 fb^{-1}

Prospects for Runs 4 and 5

A. Dainese *et al.*, CERN-2019-007





Dark SUSY model

Further limits can be estimated under additional assumptions on the dark photon production mechanism via Higgs decays

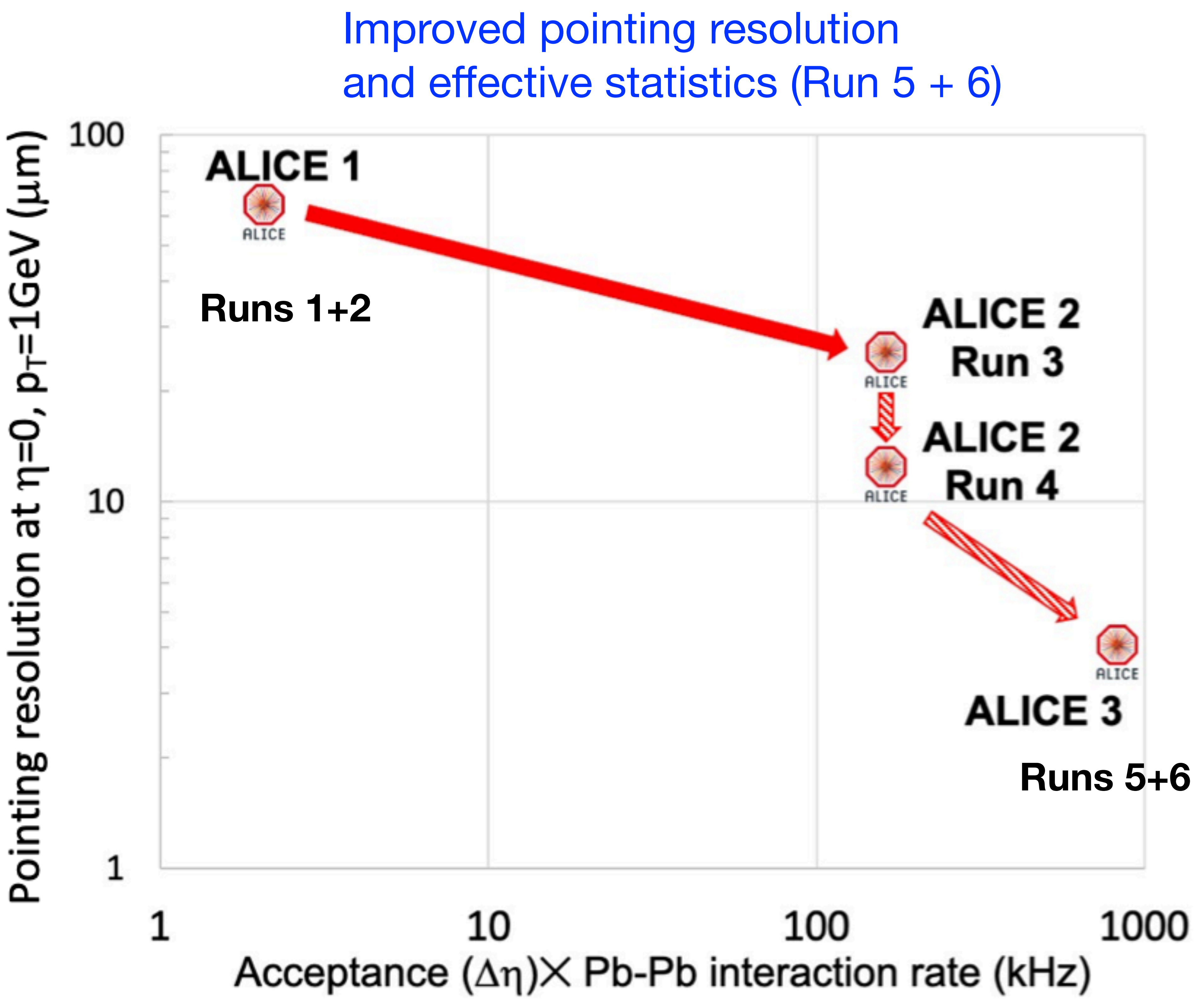
Summary

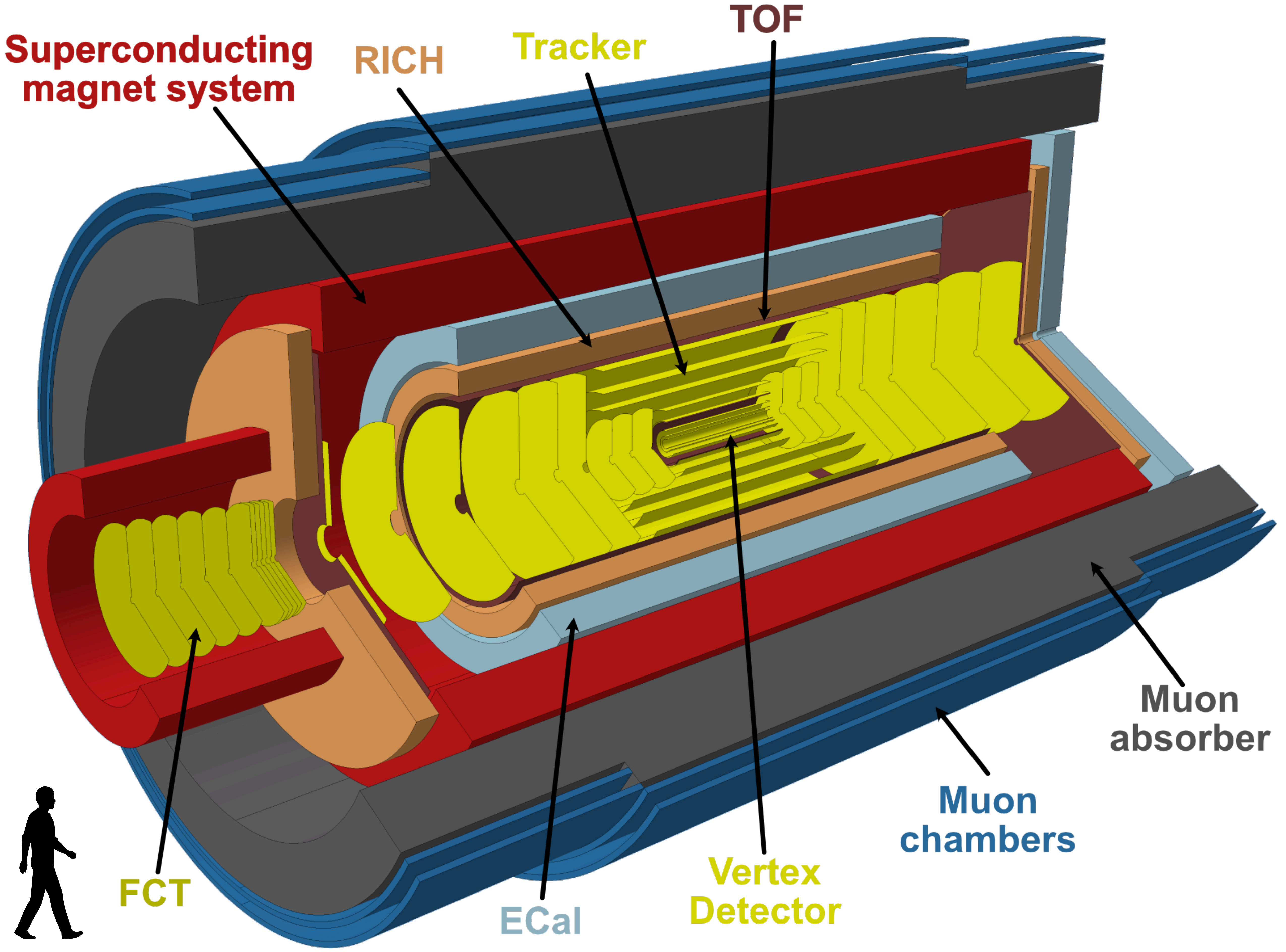
Exciting time in front of us !

Back-up

Beyond Run 4: ALICE 3

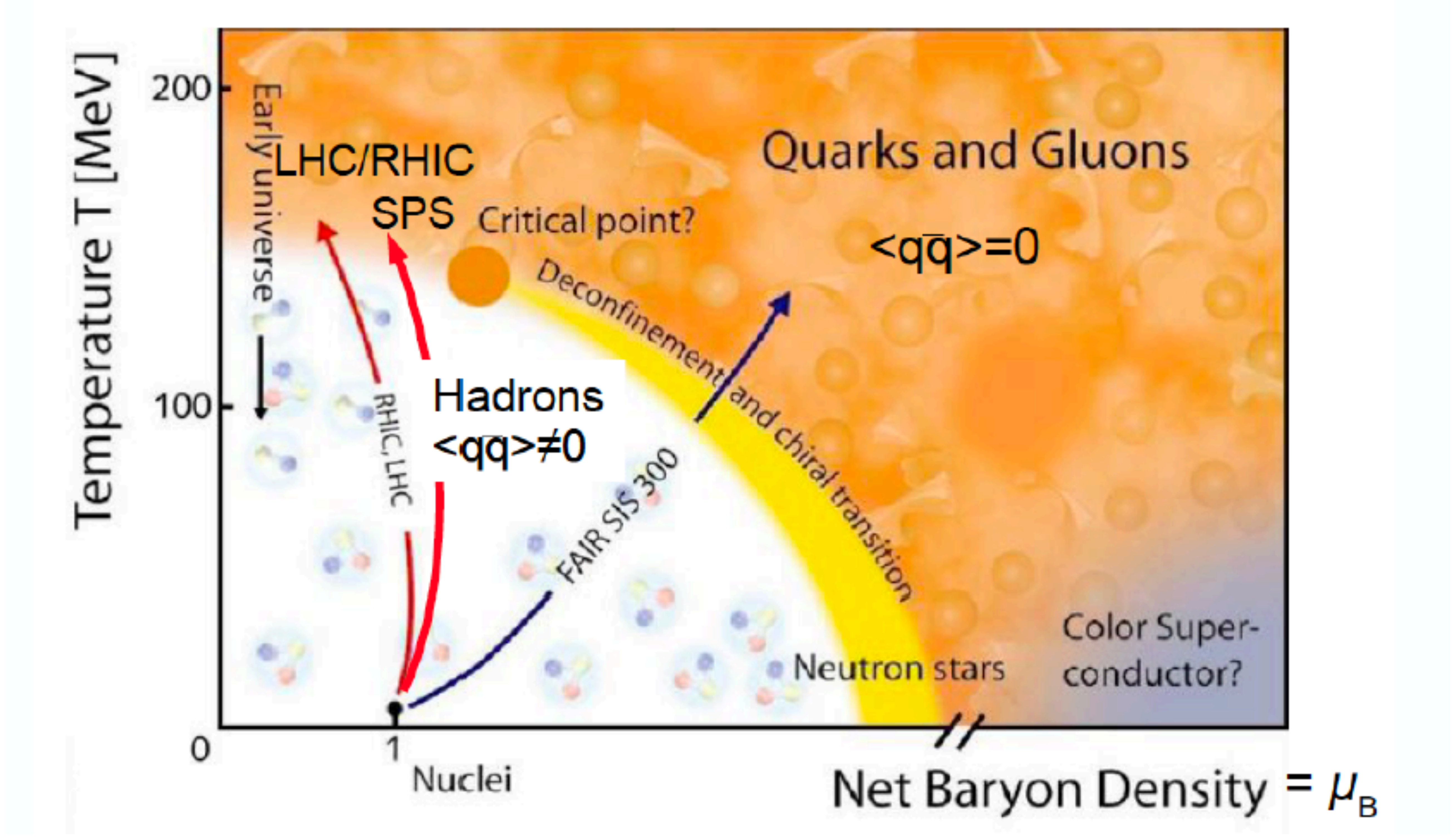
- Compact all-silicon tracker with high-resolution vertex detector
- Particle identification $\gamma, e^{\pm}, \mu^{\pm}, K^{\pm}, \pi^{\pm}$
  - Over large acceptance ($-4 < \eta < 4$)
  - Down to very low p_T





D.Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009

Nuclear matter in the universe



At high *T*, μ_B:

- **Deconfinement phase transition:** quark-gluon plasma (QGP)
  Predicted at $T_c \approx 160$ MeV for $\mu_B = 0 \rightarrow$ QGP 100 000 times hotter than the centre of the sun
- **Chiral phase transition** ($< q\bar{q} > = 0$)

Accessible through heavy-ion collisions: high T and μ_B at the LHC

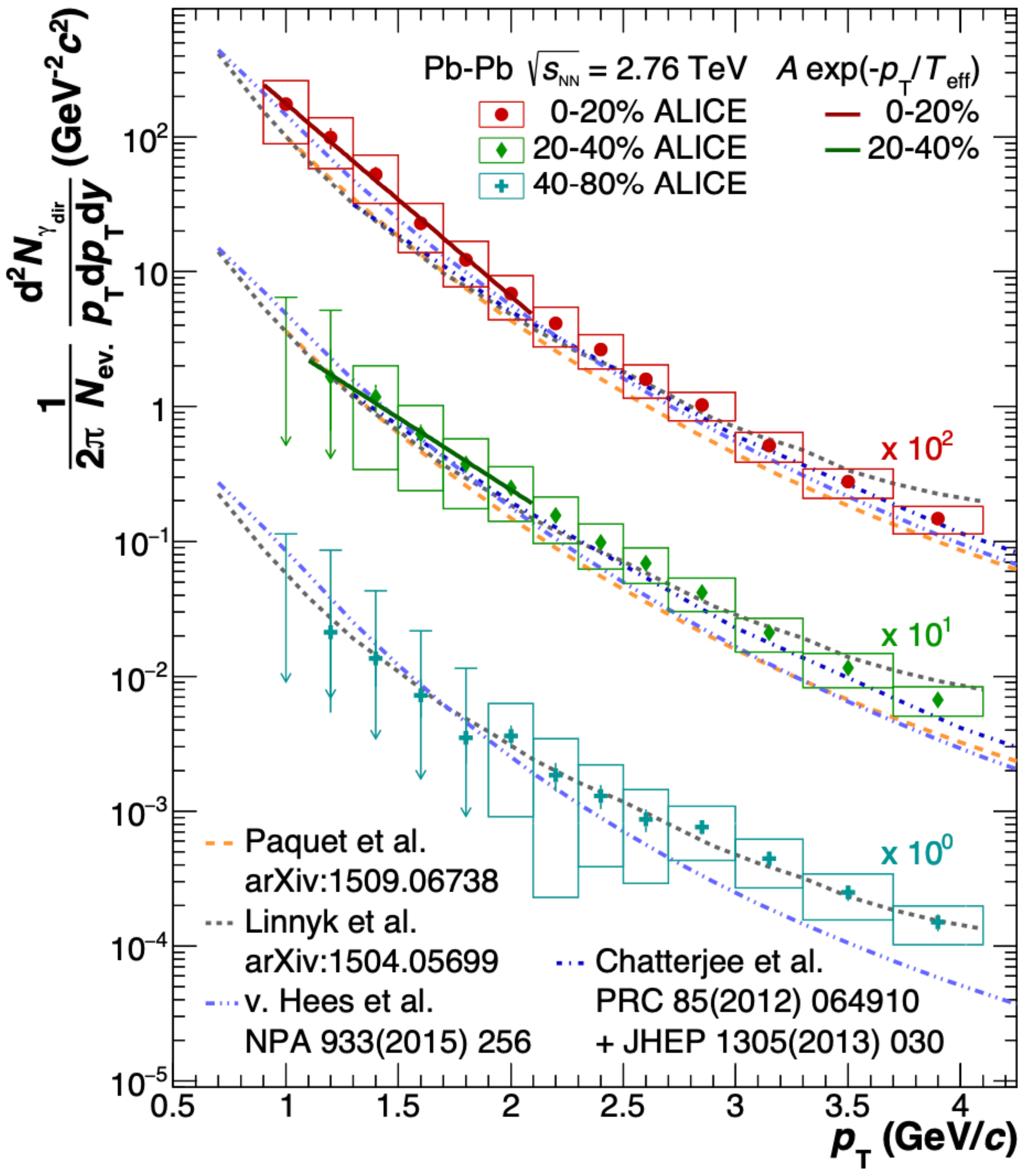
Direct real photons (Run 2)

Same measurements at $\sqrt{s_{NN}}$ = 2.76 TeV:

0-20%: Inverse slope $T_{\text{eff}} = 297 \pm 12(\text{stat}) \pm 41(\text{syst})$
Models allow then to estimate T of medium

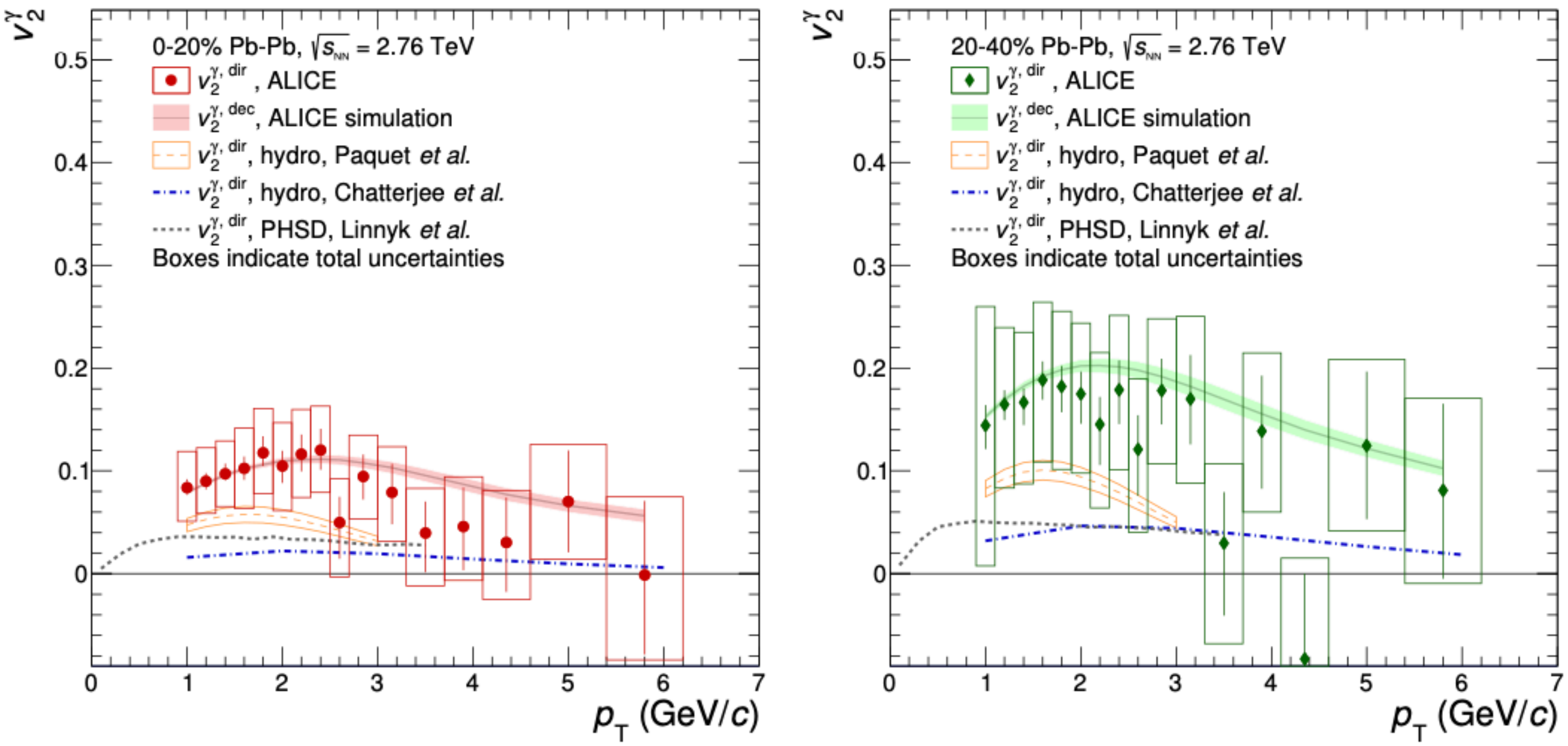
→ Need to reduce uncertainties (yield, v_2) to constrain models

Pb—Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



Direct real photons (Run 2)

Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV



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

Direct real photon via γ^* (Run 2)

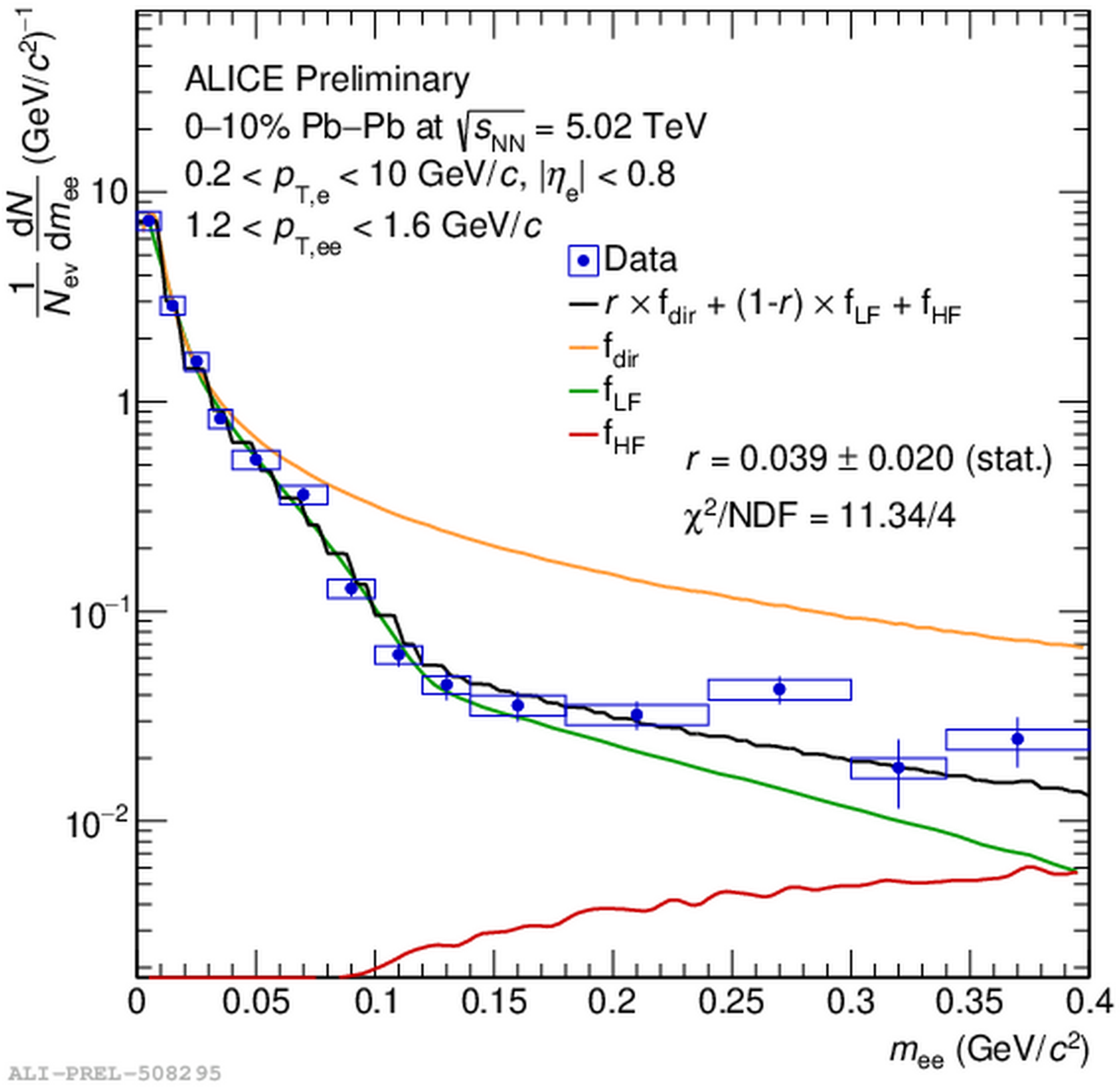
- Assume excess comes from virtual direct photons

- Extract ratio of direct photon γ_{dir} to inclusive photon γ_{incl} via template fit of m_{ee} distributions:

$$d\sigma/dm_{\text{ee}} = r \times f_{\text{dir}} + (1-r) \times f_{\text{LF}} + f_{\text{HF}}$$

Only free parameter $r = (\gamma^*_{dir}/\gamma^*_{inc})_{m_{\text{ee}}\to 0} = (\gamma_{dir}/\gamma_{inc})$

- Fit performed for $m_{\text{ee}} > 140$ MeV/c^2 to suppress π^0 background



Direct photon template f_{dir} described by Kroll-Wada formula

N.M. Kroll and Walter Wada, Phys. Rev. 98 (1955) 1355

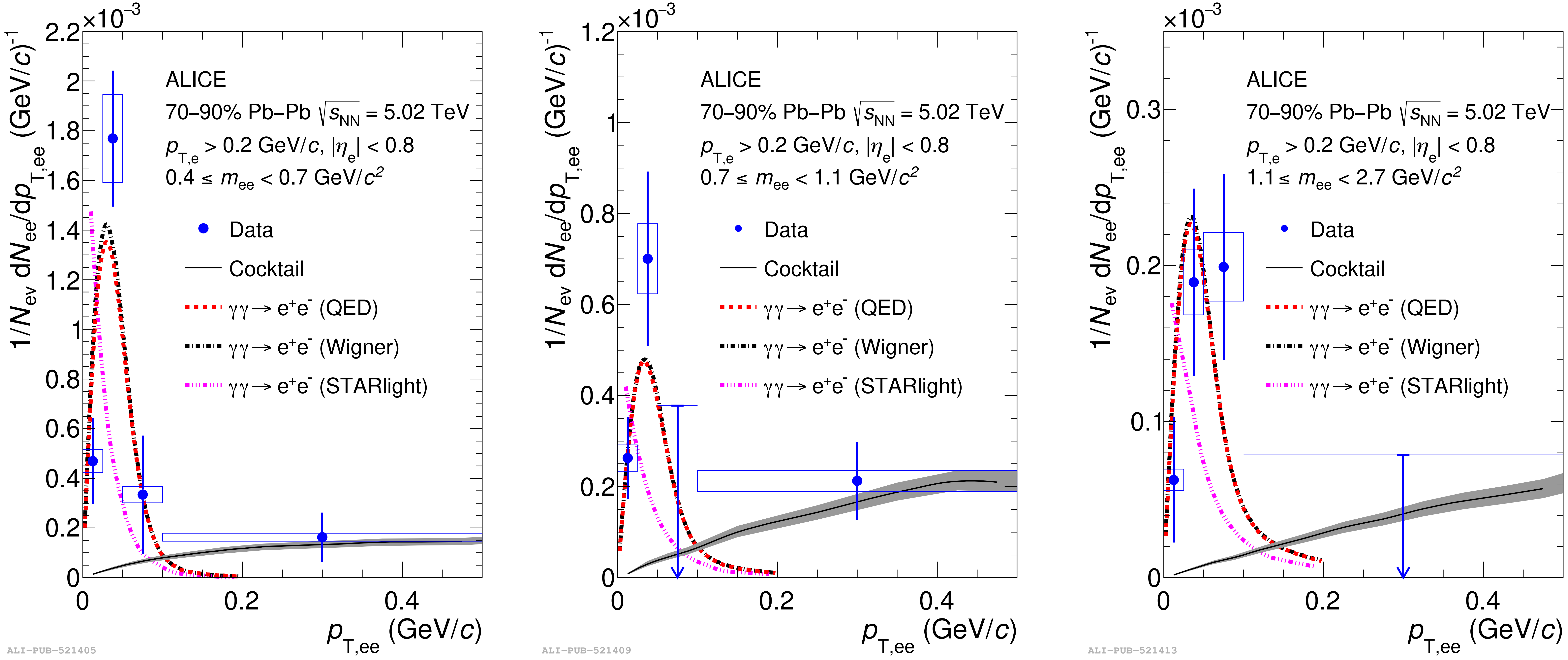
$\gamma\gamma \to e^+e^-$ production in peripheral Pb—Pb collisions

New

ALICE

arXiv:2204.11732

$0.4 < m_{ee} < 0.7$ GeV/c^2 | $0.7 < m_{ee} < 1.1$ GeV/c^2 | $1.1 < m_{ee} < 2.7$ GeV/c^2



$\gamma\gamma \to e^+e^-$ predictions:

QED:
W. Zha *et al.*,
PLB 800 (2020) 135089
J. D. Brandenburg *et al.*,
EPJ A 57 (2021) 299

Wigner:
M. Klusek-Gawenda *et al.*,
PLB 814 (2021) 136114

STARlight:
S.R. Klein *et al.*
CPC 212 (2017) 258
S.R. Klein,
PRC 97 (2018) 054903

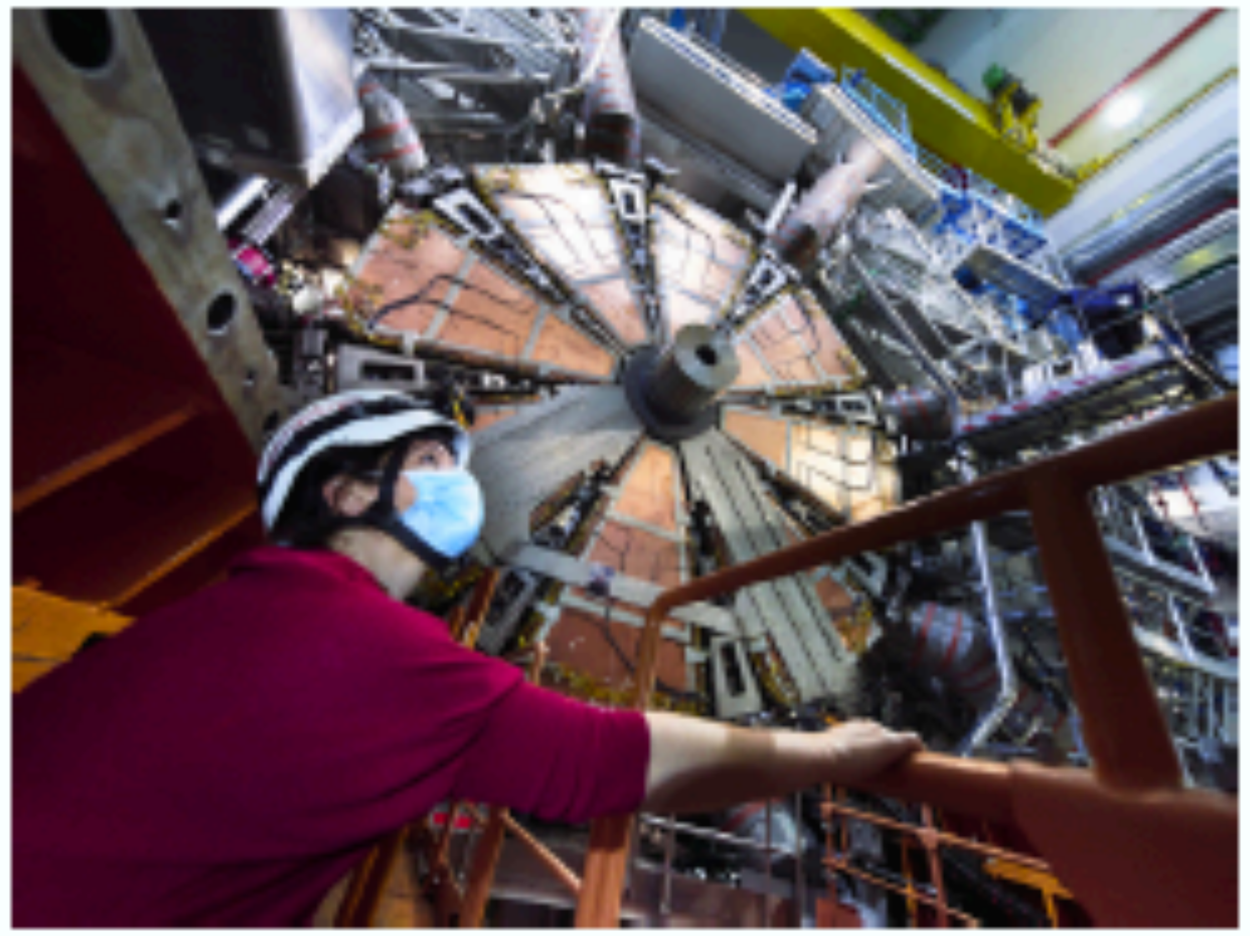
- **Peak observed at low $p_{T,ee}$** in 70–90% peripheral Pb—Pb collisions
- Data described by **QED & Wigner predictions with impact parameter (*b*) dependence of γ transverse momentum**
- **STARLIGHT** ($p_{T,ee}$ shape independent of *b*) **disfavoured** by the data

ATLAS phase I upgrades

→ Z. Citron (Wed 11:50)

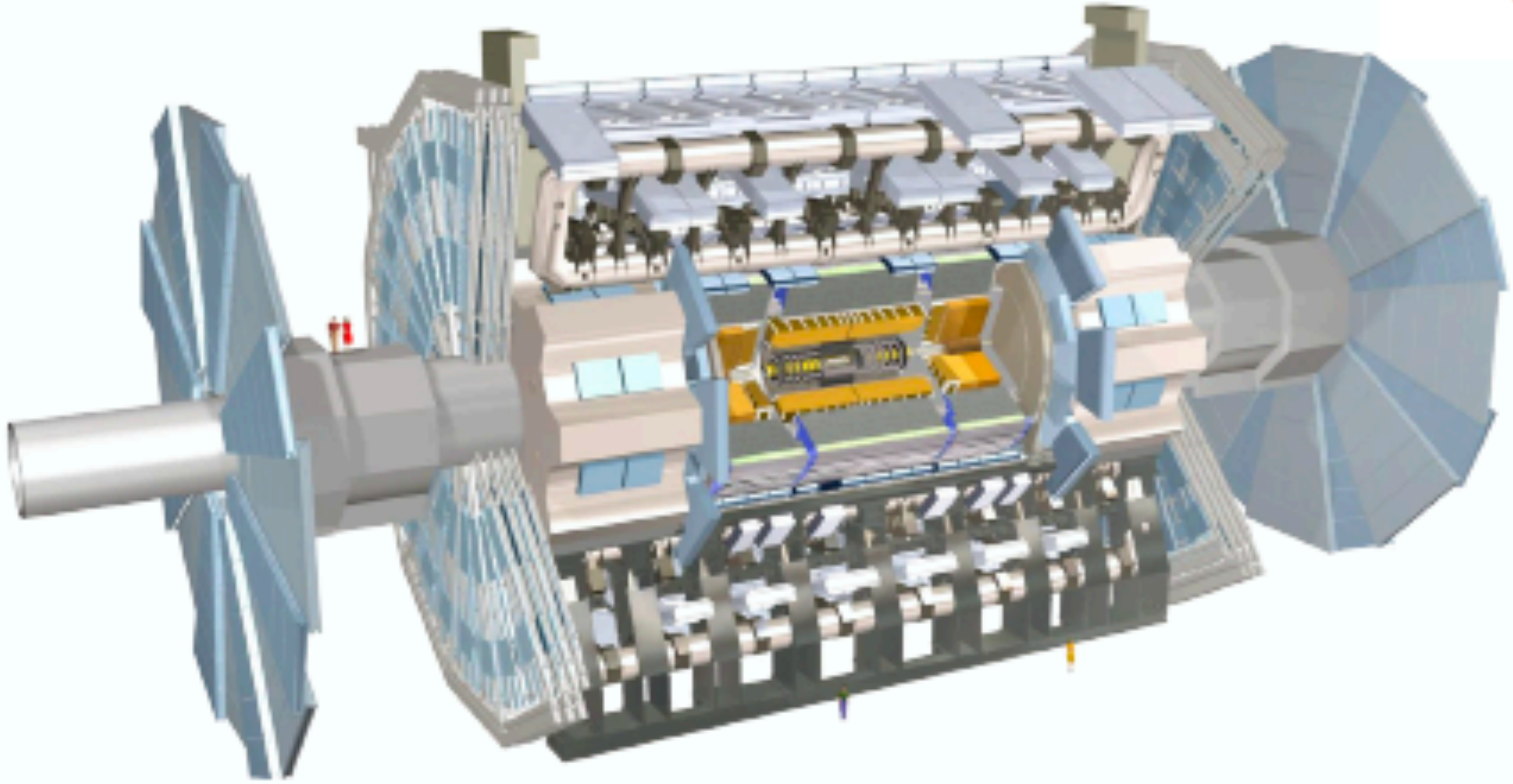
Muon system

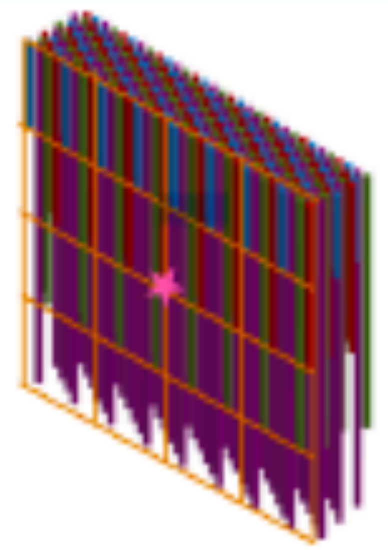
- **New Small Wheels** installed → sTGC + MicroMegas



Trigger and DAQ

- L1 and HLT improvements



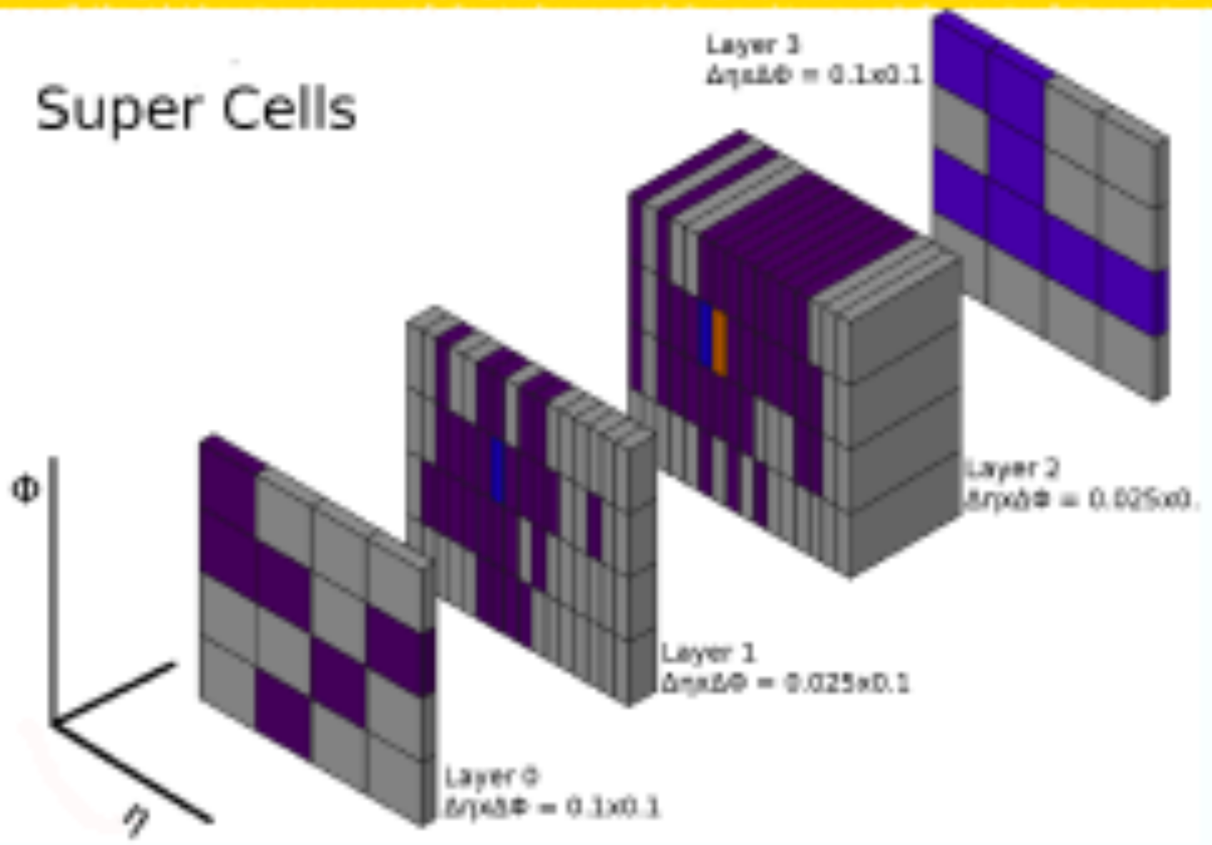


ZDC

- Fused silica rods for radiation tolerance
- On-detector processing
- Reaction plane detector

LAr calorimeter

- **Segmented super-cells:** shower-shape discrimination at trigger level



➡ **Increased statistics**
➡ **Improved ZDC**

ATLAS phase II upgrades

→ Z. Citron (Wed 11:50)

LAr calorimeter

- **Segmented super-cells:** shower-shape discrimination at trigger level

Trigger and DAQ

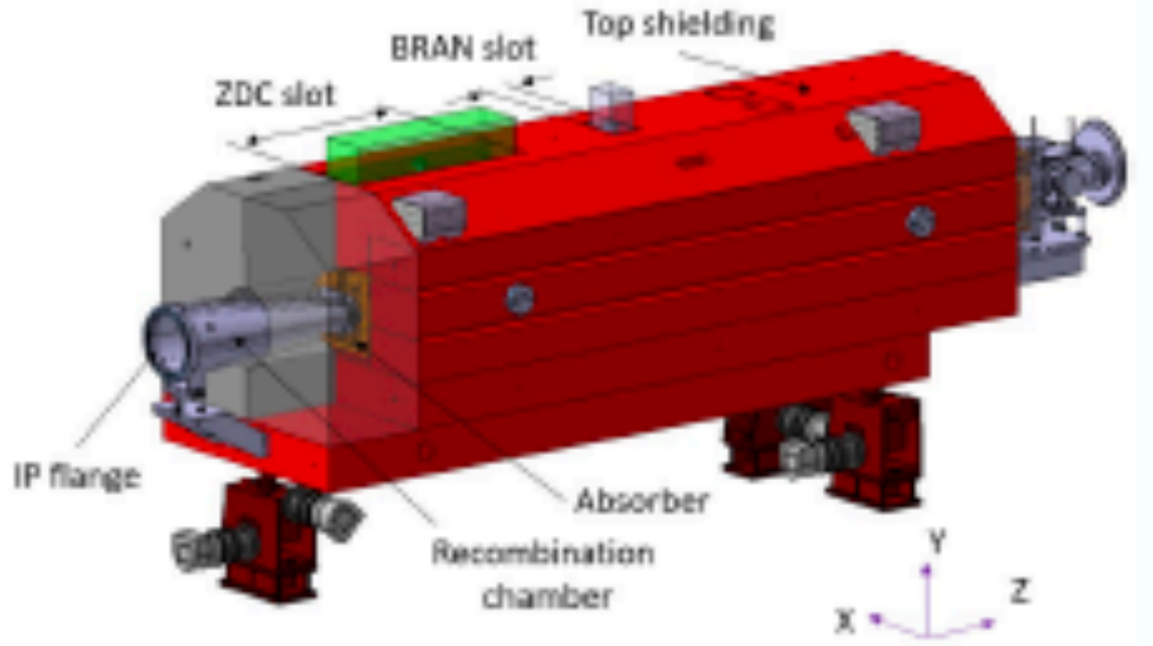
- L1 and HLT improvements
- Further upgrades

Electronics upgrades

Luminosity detectors

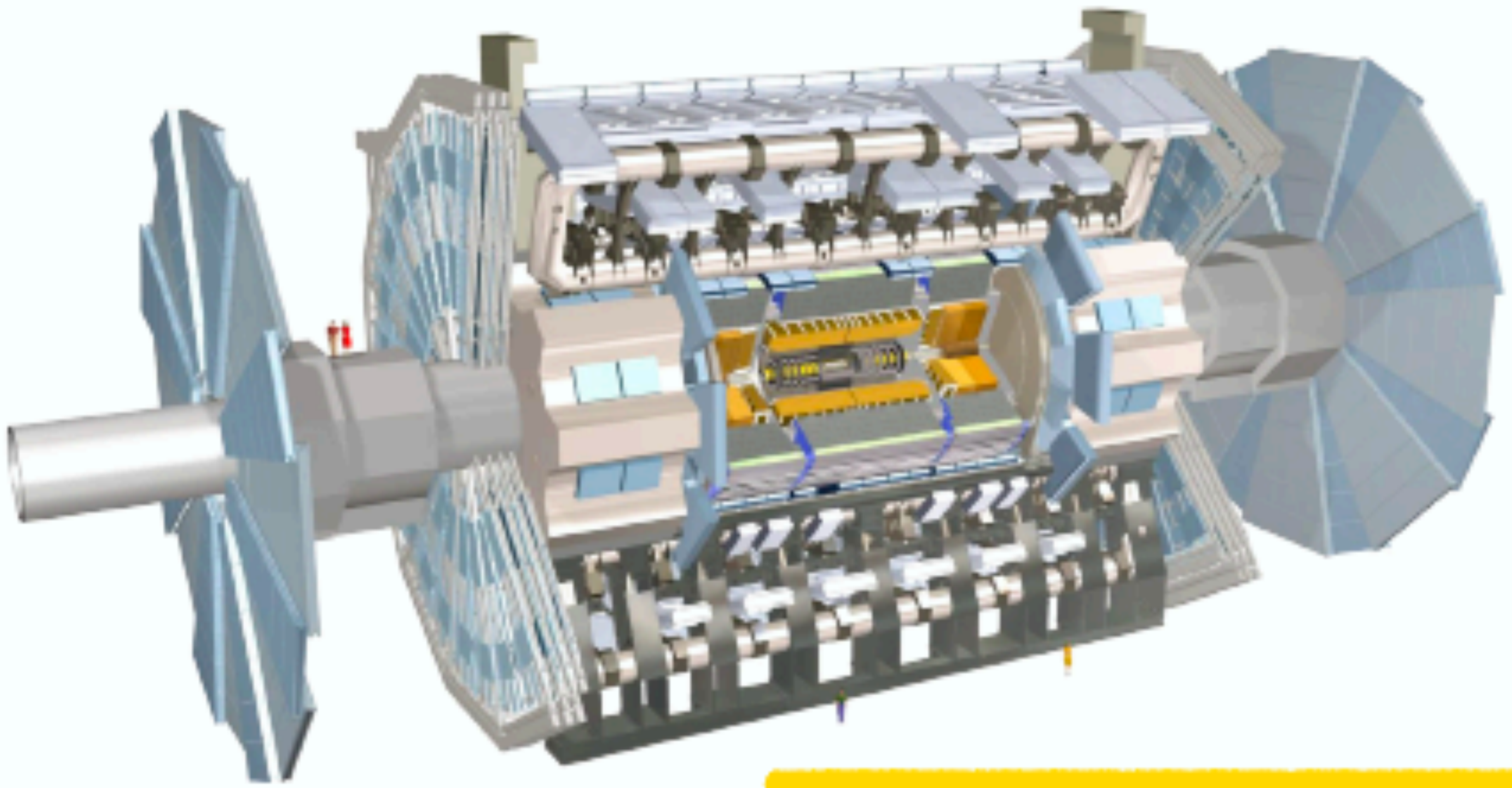
HL-ZDC

- JZCaP (jointly with CMS)
- adapt to new optics
- increase radiation hardness
- Reaction plane detector



High-granularity timing detector

- Based on LGADs
- PID with $\sigma_{TOF} \approx 35$ ps
- Baseline trigger for HI

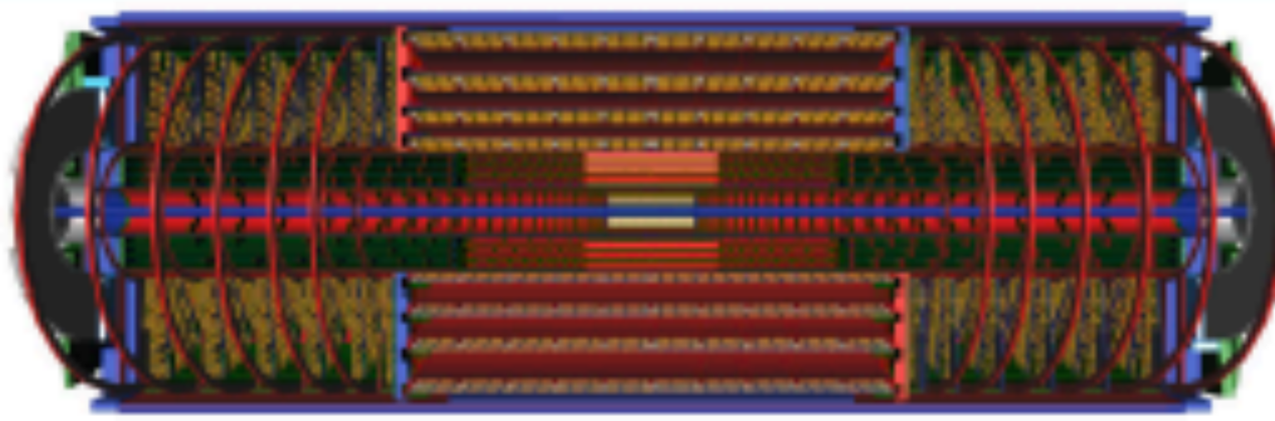


New Inner Tracker (ITk)

- hybrid silicon pixel and strip sensors
- coverage up to $|\eta| < 4$

Endcap calorimeters

- higher granularity



Muon system

- **New Small Wheels** installed → sTGC + MicroMegas
- **New muon chambers**

➡ **Extend tracker acceptance to $|\eta| < 4$**
➡ **Time-of-flight PID $2.5 < |\eta| < 4$**
➡ **Endcap calorimeters with higher granularity**

CMS phase I upgrades

Tracker

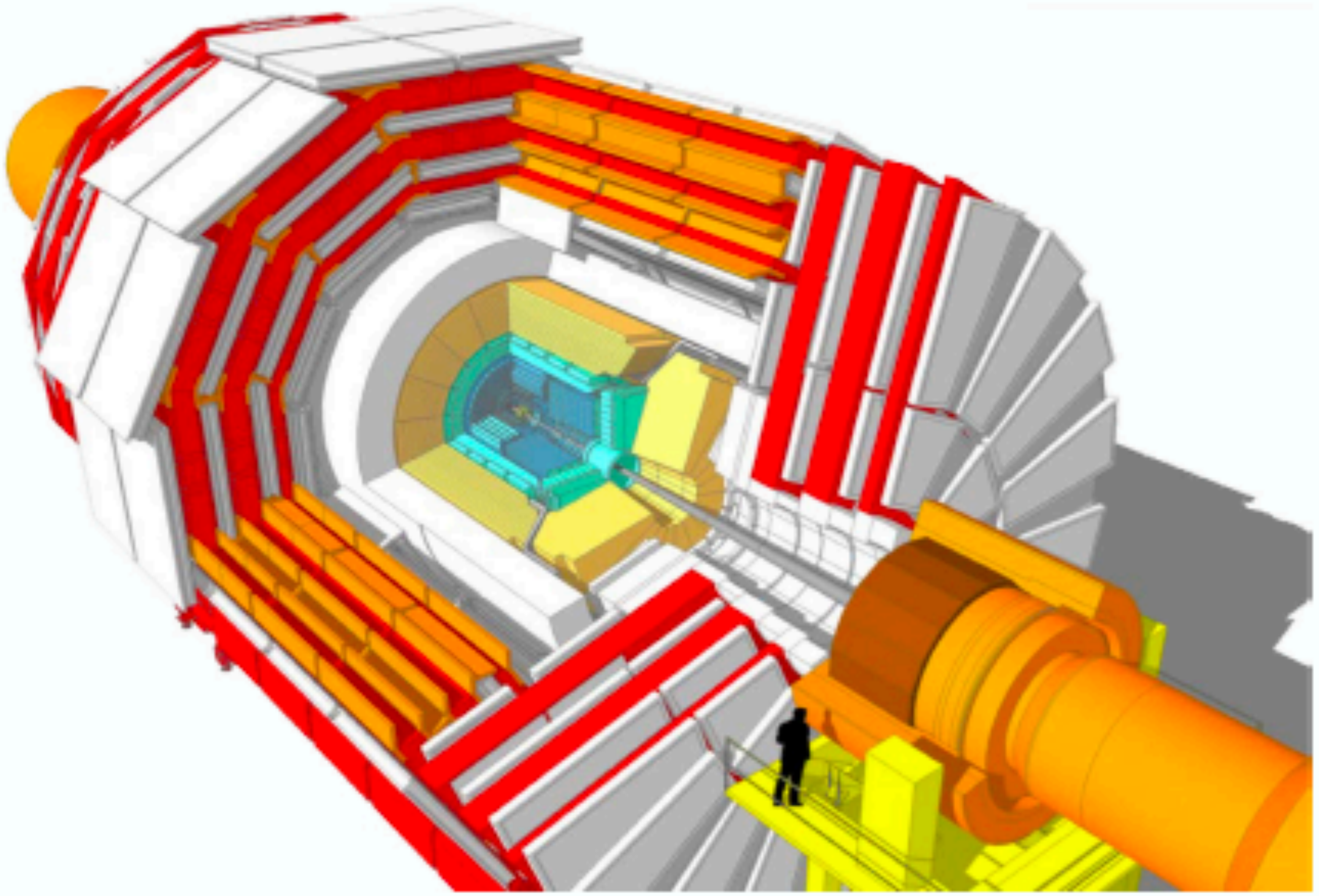
- Phase-I pixel detector:
  3 → 4 barrel layers
  2 → 3 forward disks
  30 → 22.5 mm beampipe

HCal

- HPD → SiPMs
- Upgraded readout

Trigger

- FPGAs for L1 trigger
- Inclusion of CSC and GEM for track algorithm for L1
- GPU modules for HLT



Forward muon system

- 144 GEM chambers installed
- new frontend electronics for CSC endcaps

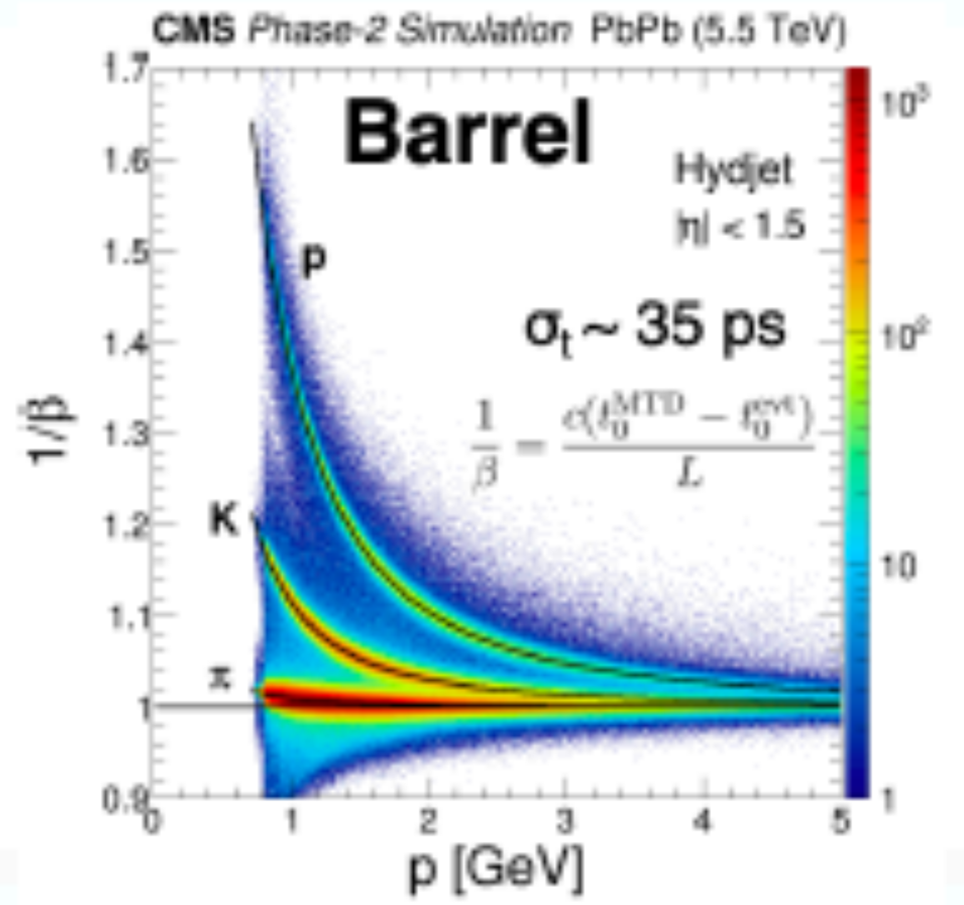
→ Increased bandwidth and larger MB statistics

CMS phase II upgrades

→ A. Stahl (Thu 15:20)

MIP timing detector

- barrel: LYSO + SiPMs
- endcaps: LGADs
- $\sigma_{TOF} \approx 30$ ps



Tracker

- inner: hybrid silicon pixels
- outer: hybrid silicon pixels + strips

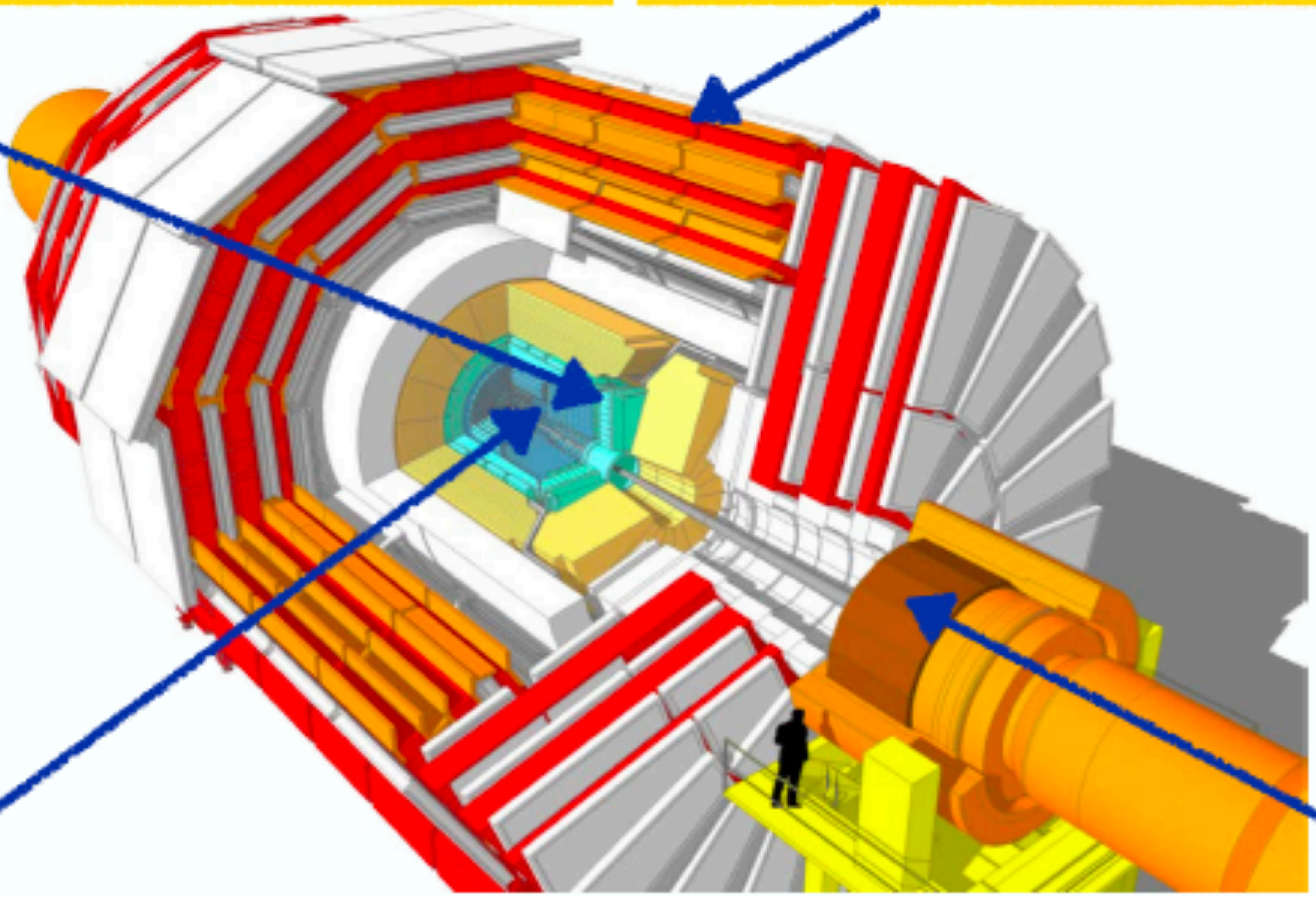
HCal

- HPD → SiPMs

L1 trigger, HLT, DAQ

Luminosity detectors

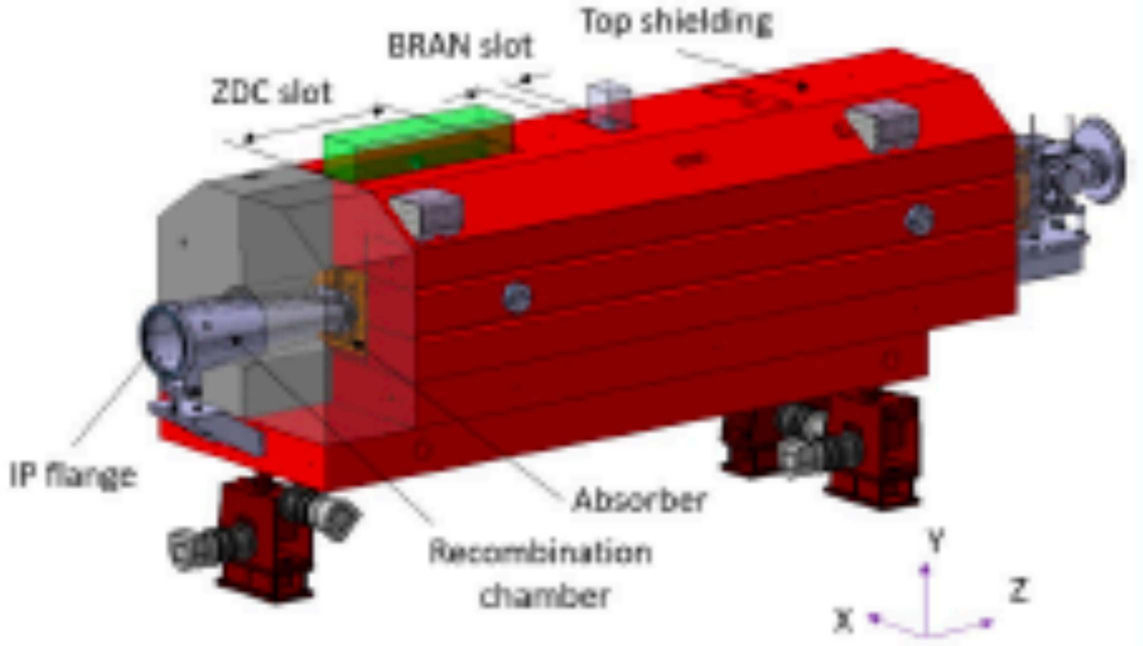
New readout for muon system



- ➟ Charged particle tracking up to $|\eta| < 4$, muons up to $|\eta| < 3$
- ➟ Time-of-flight PID up to $|\eta| < 3$
- ➟ High-precision vertexing
- ➟ Wide coverage calorimetry

HL-ZDC

- JZCaP (jointly with CMS)
- adapt to new optics
- increase radiation hardness
- Reaction plane detector



Endcap calorimeter

- **High-granular ECal + HCal → 4d showers ($\sigma_t \approx 20$ ps)**

Forward muon system

- All GEM chambers
- new frontend electronics for CSC endcaps

LHCb upgrade I(a)

→ S. Mariani (Wed 11:30)

RICH

- RICH1 (C_4F_{10}) renewed, RICH2 (CF_4) upgraded
- HPD → MaPMTs
- new readout ASIC (CLARO)

Readout and data processing

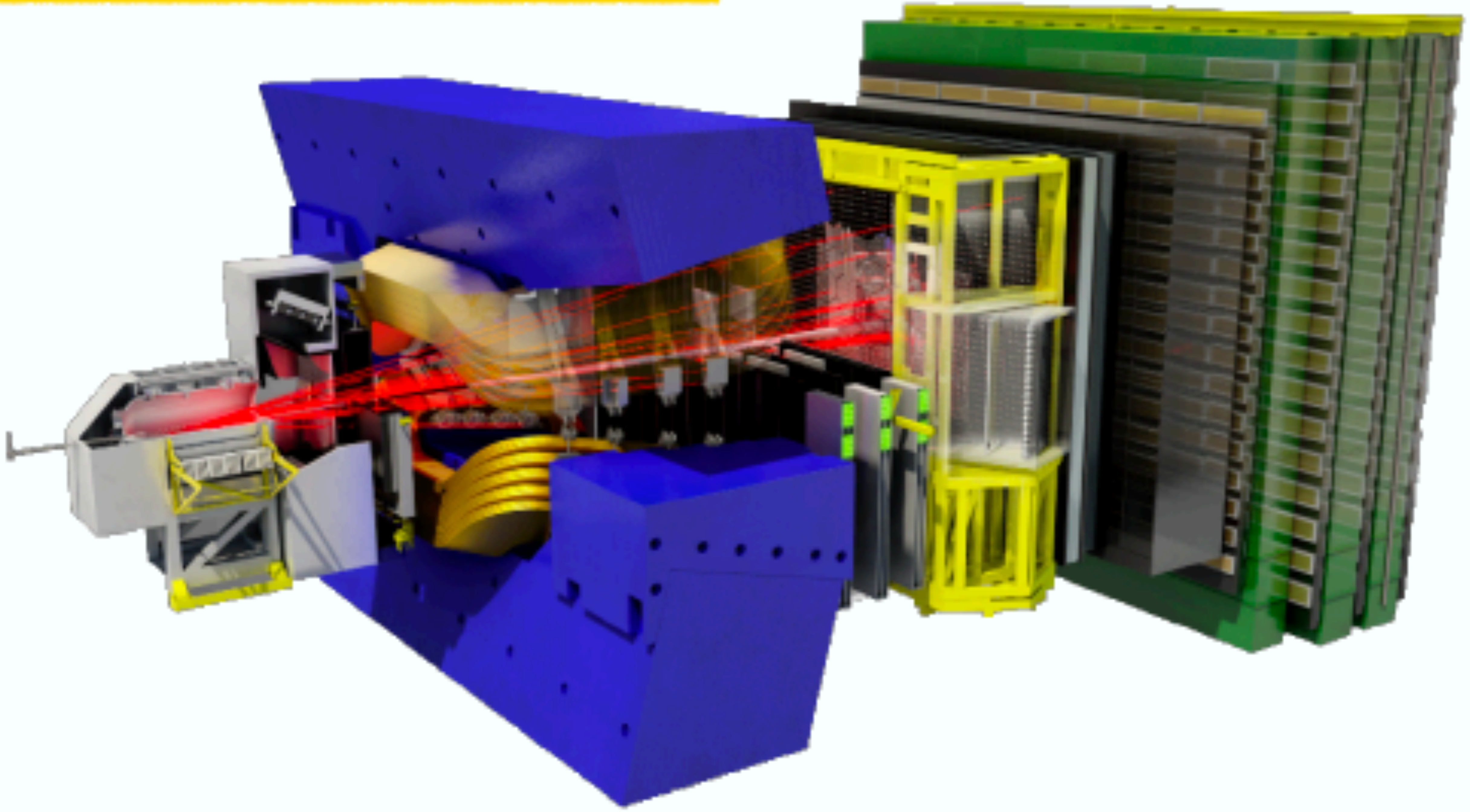
- sw trigger on GPUs → readout at 40 MHz

Muon stations

- M1 (GEM) removed
- new electronics (triggerless)

Vertex Locator

- new VeloPix sensor
- closer to beam (8.1 mm → 5.1 mm)
- thin RF foil



Tracking

- Upstream tracker → Silicon micro-strips
- SciFi tracker (new) → SiPM readout

SMOG 2

- parallel operation with pp
- higher pressure
- also non-noble gases

Calorimeters

- new electronics (triggerless, non-zs data)
- reduced PMT gain

➡ **50 kHz Pb-Pb (> 30 % centrality)**
➡ **Improved vertexing**
➡ **Higher luminosities for fixed target**

LHCb upgrade Ib

→ S. Mariani (Wed 11:30)

RICH

- RICH1 (C_4F_{10}) renewed, RICH2 (CF_4) upgraded
- HPD → MaPMTs
- new readout ASIC (CLARO)
- timing

Readout and data processing

- sw trigger on GPUs → readout at 40 MHz

Infrastructure for Run 5 & 6

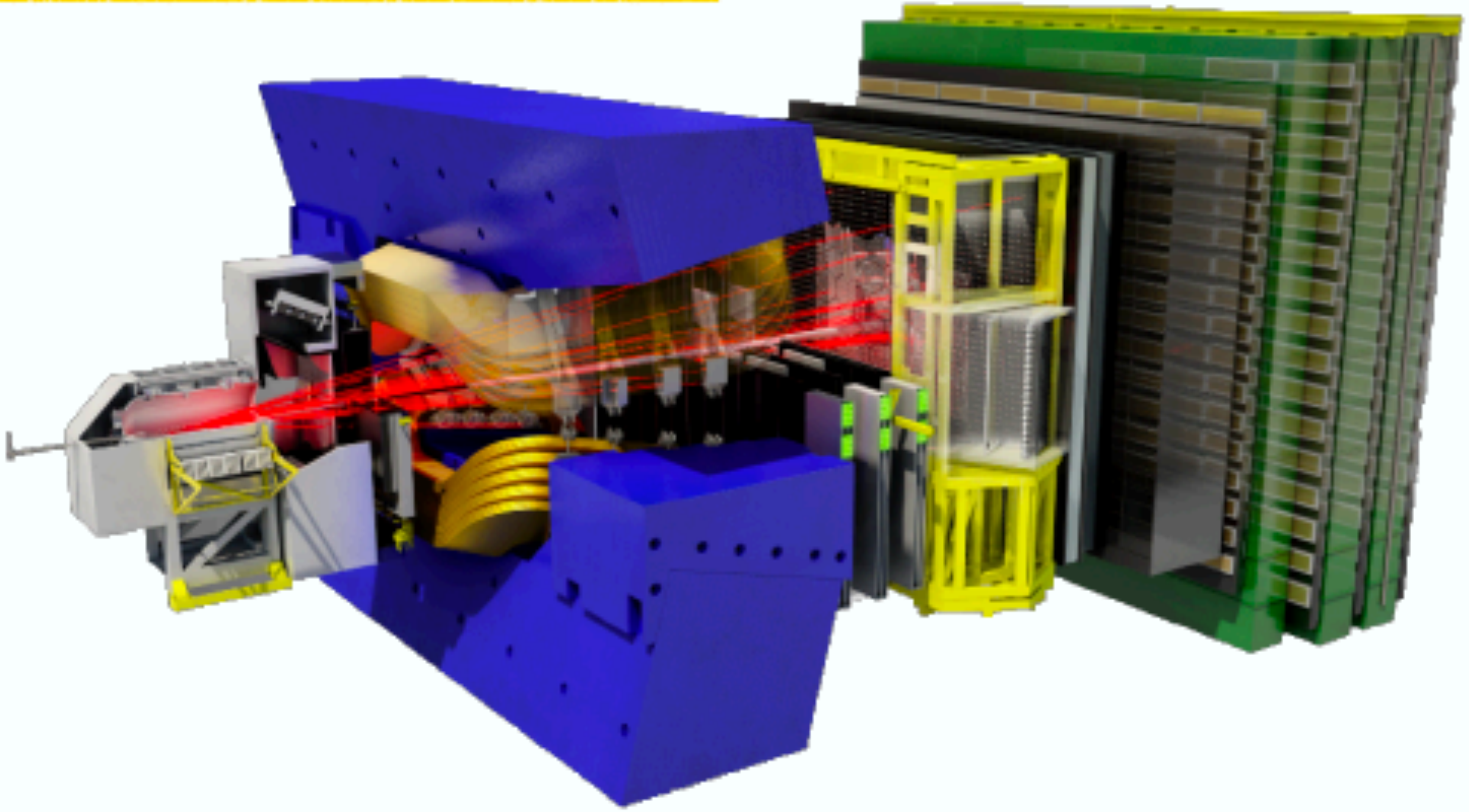
- engineering, mechanical support, shielding

Muon stations

- M1 (GEM) removed
- new electronics (triggerless)

Vertex Locator

- new VeloPix sensor
- closer to beam (8.1 mm → 5.1 mm)
- thin RF foil



Tracking

- Upstream tracker
- SciFi tracker → replace two inner modules (possibly with MAPS)
- Magnet stations (possibly) → p_T below 5 GeV/c

SMOG 2

- parallel operation with pp
- higher pressure
- also non-noble gases

Calorimeters

- new electronics (triggerless, non-zs data)
- reduced PMT gain

➞ **50 kHz Pb-Pb (> 30 % centrality)**
➞ **Improved vertexing**
➞ **Higher luminosities for fixed target**

[CERN-LHCC-2021-012]

LHCC review of Framework TDR completed in March 2022

LHCb Upgrade II

→ S. Mariani (Wed 11:30)

RICH

- RICH1 and RICH2
- precision timing

TORCH

- Time-of-flight wall
- precision timing

Run 5 infrastructure

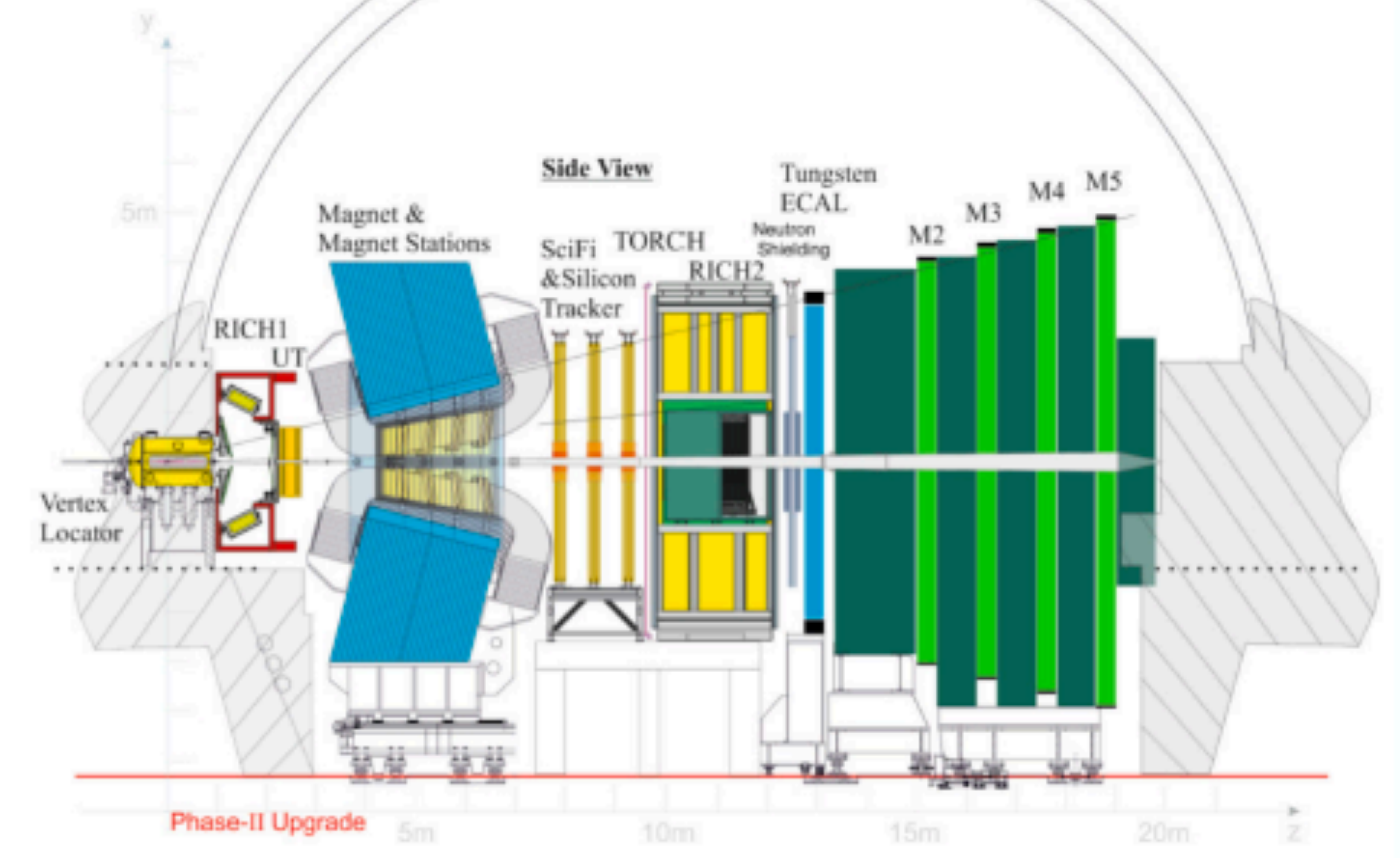
- engineering, mechanical support, shielding

Muon stations

- M2 - M5
- additional shielding (instead of HCal)

Vertex Locator

- new VELO
- precision timing



Tracking

- new Upstream Tracker (timing)
- Mighty Tracker (SciFi + silicon)
- Magnet stations (possibly) → p_T below 5 GeV/c

Fixed target

- possible extension with polarised gas target, solid target

Calorimeters

- SPACAL or Shashlik
- precision timing

→ **No centrality limitation for AA**

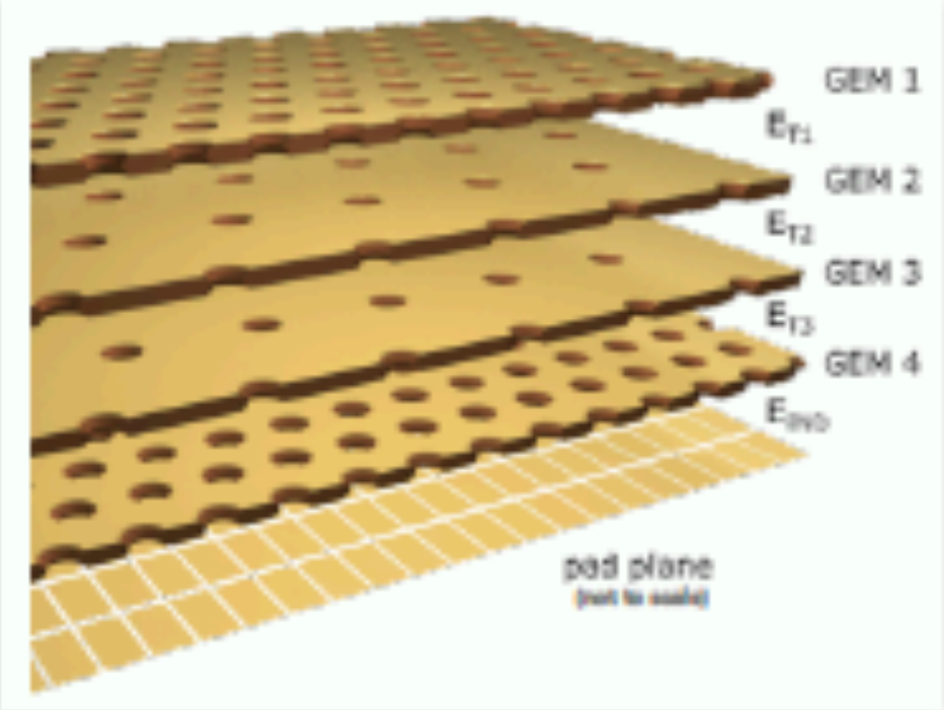
→ **Excellent vertexing capabilities**

ALICE 2 upgrade

→ A. Alkin (Thu 15:40)

Time Projection Chamber

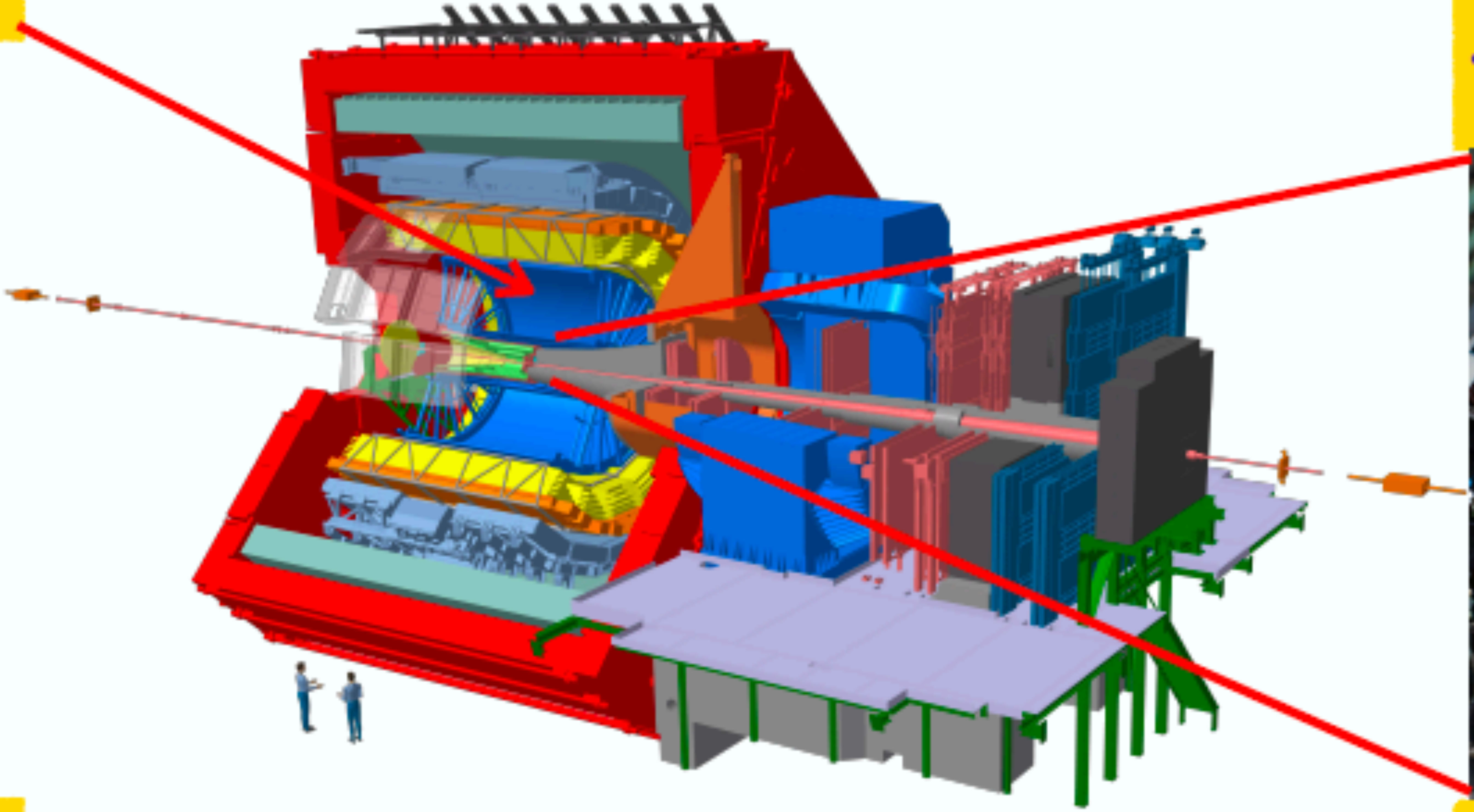
- new readout chambers: MWPC → GEM



Consolidation and readout upgrade of all subsystems

Fast Interaction Trigger

- new detectors



Inner Tracking System

- 3 + 2 + 2 layers of MAPS (~10 m²)
- improved vertexing at higher rates

Integrated on-/off-line system

- continuous readout
- GPU-based reconstruction parallel with data taking
- online event selection

➡ **Continuous readout** with Pb-Pb @ 50 kHz

➡ **Better vertexing** (central and forward)

Muon Forward Tracker

- MAPS-based tracker installed
- vertexing in forward acceptance (muon arm)

ALICE 2.1 upgrade

→ S. Scheid (Thu 16:00)

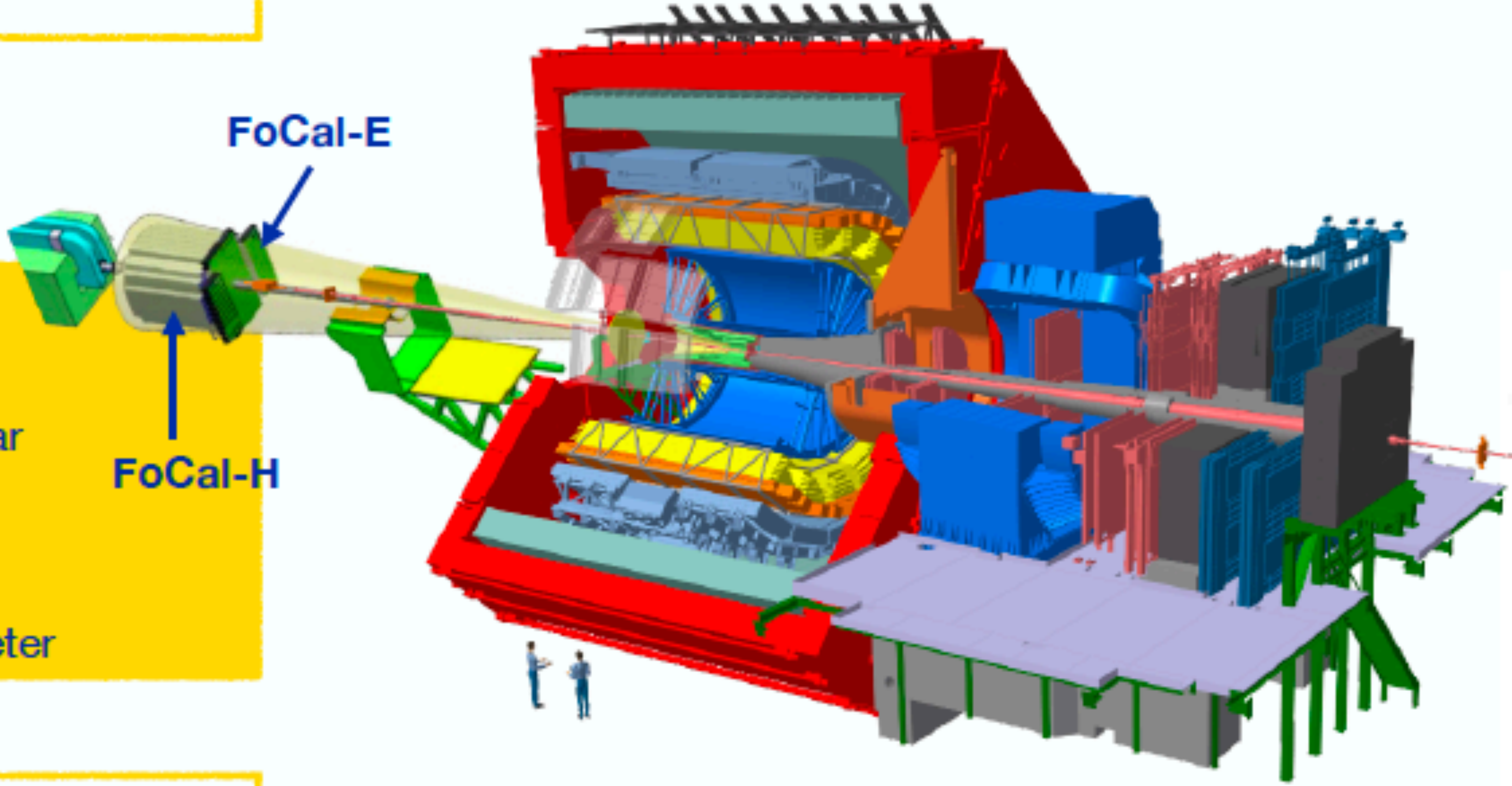
Time Projection Chamber
- new readout chambers: **MWPC → GEM**

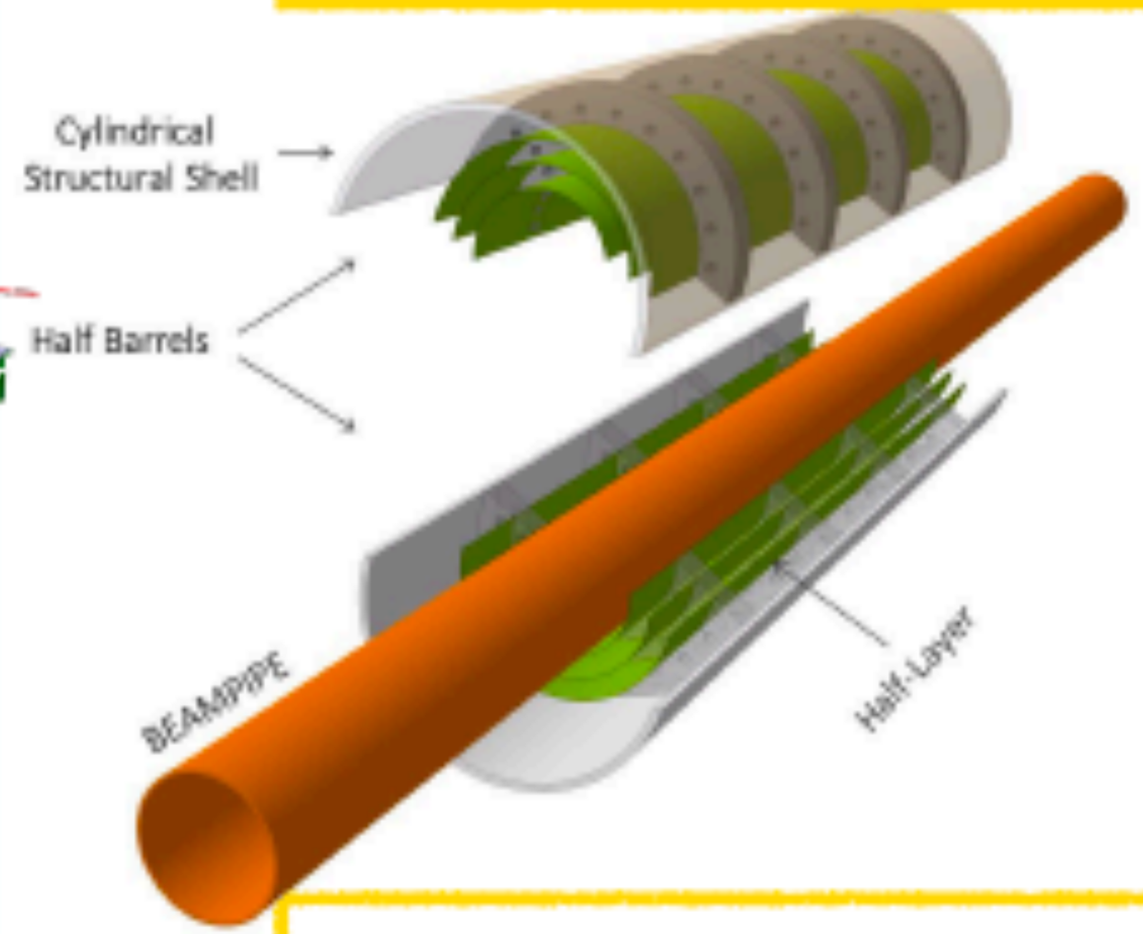
Consolidation and readout upgrade of all subsystems

Fast Interaction Trigger
- new detectors

Inner Tracking System
- 3 + 2 + 2 layers of MAPS (~10 m²)
- improved vertexing at higher rates
- **ITS3 → Bent, wafer-scale monolithic pixel sensors for 3 innermost layers**

FoCal
- **FoCal-E:** Si-W high-granular elm. calorimeter
- **FoCal-H:** Cu-fibre hadronic calorimeter





Integrated on-/off-line system
- **continuous readout**
- **GPU-based reconstruction** parallel with data taking
- online event selection

→ **Continuous readout** with Pb-Pb @ 50 kHz
→ **Better vertexing** (central and forward)

Muon Forward Tracker
- **MAPS-based tracker** installed
- vertexing in forward acceptance (muon arm)

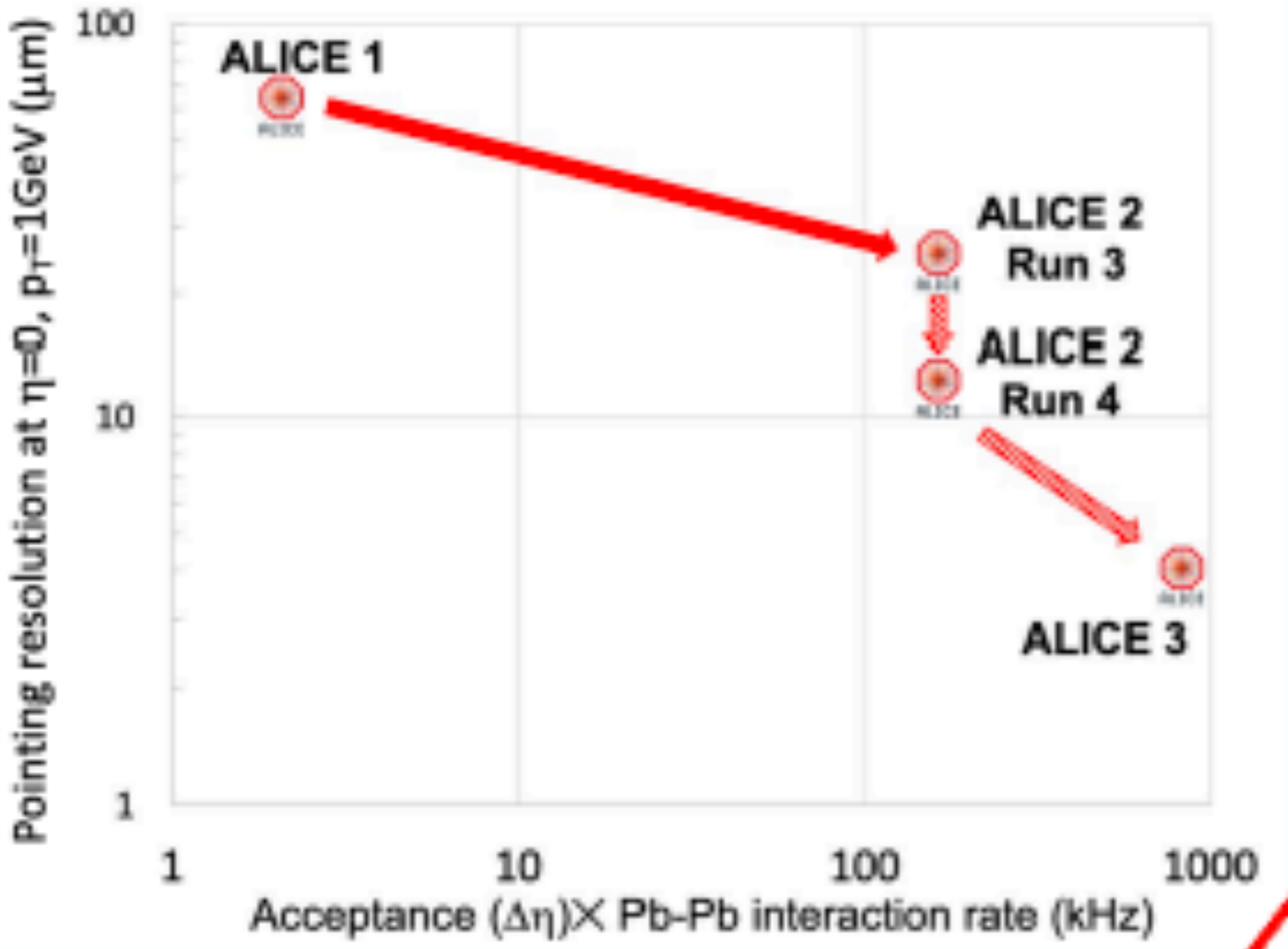
[CERN-LHCC-2022-009]

LHCC review of Letter of Intent completed March 2022

ALICE 3 upgrade

→ S. Scheid (Thu 16:00)

Vertex detector
- Retractable detector $R_{in} \approx 5$ mm
- Wafer-scale monolithic CMOS sensors

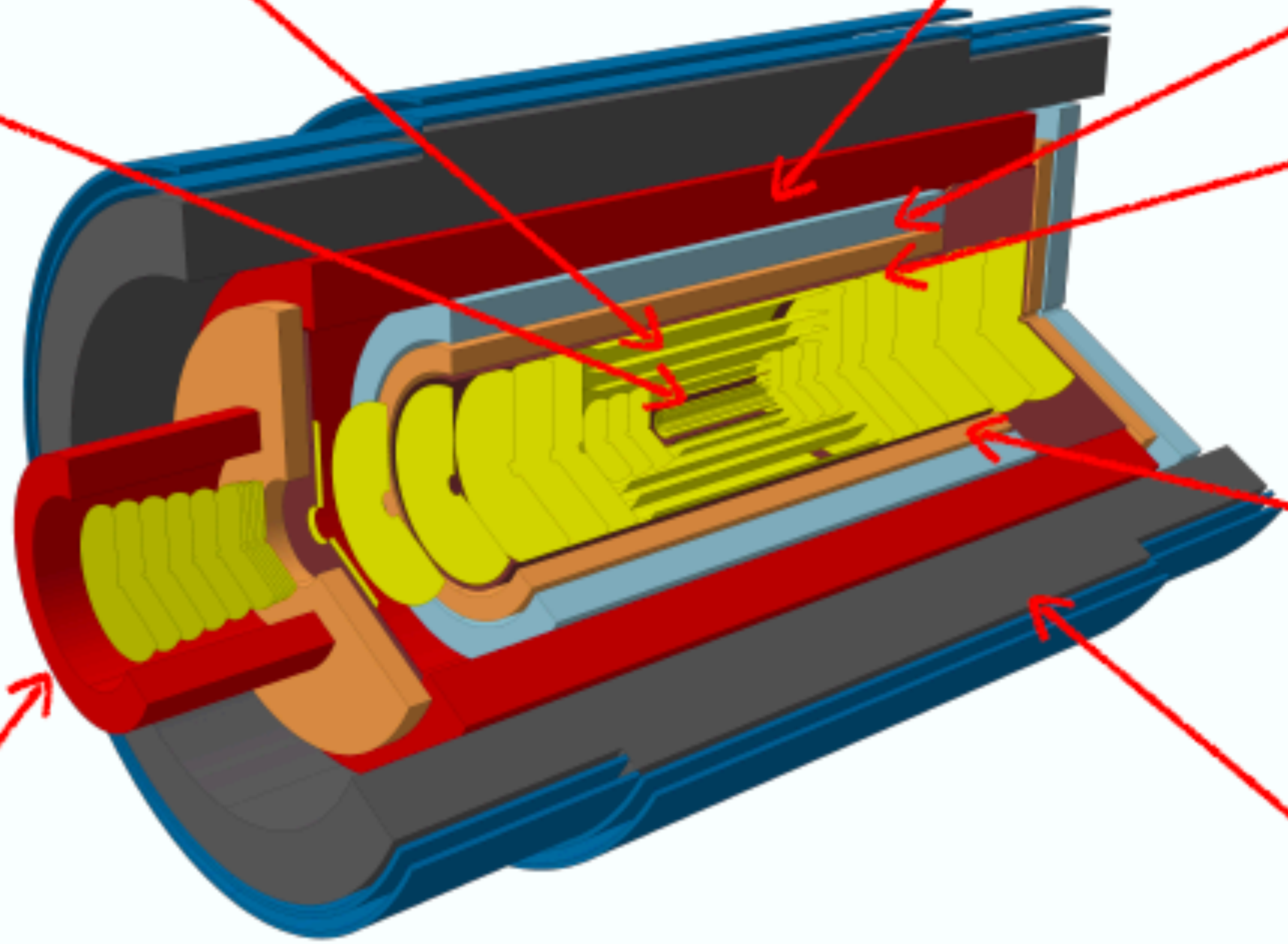


Tracker
- Monolithic CMOS sensors

Superconducting magnet system

Elm. calorimeter
- PbWO4 in central region
- Pb/Sci for large acceptance

Time-of-flight detector
- monolithic CMOS sensors with gain layer



Ring-imaging Cherenkov detector
- Aerogel radiator
- SiPM read-out

Muon ID
- Iron absorber
- Scintillating bars, WLS, SiPM

Forward Conversion Tracker
- Tracking disks (MAPS)

➟ **Tracking and PID over large acceptance**
➟ **Excellent vertexing**
➟ **Continuous readout**