Electromagnetic Probes
Dileptons – Experiments

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Excellence Cluster Universe - TU München

H-QM Helmholtz Research School – Lecture Week
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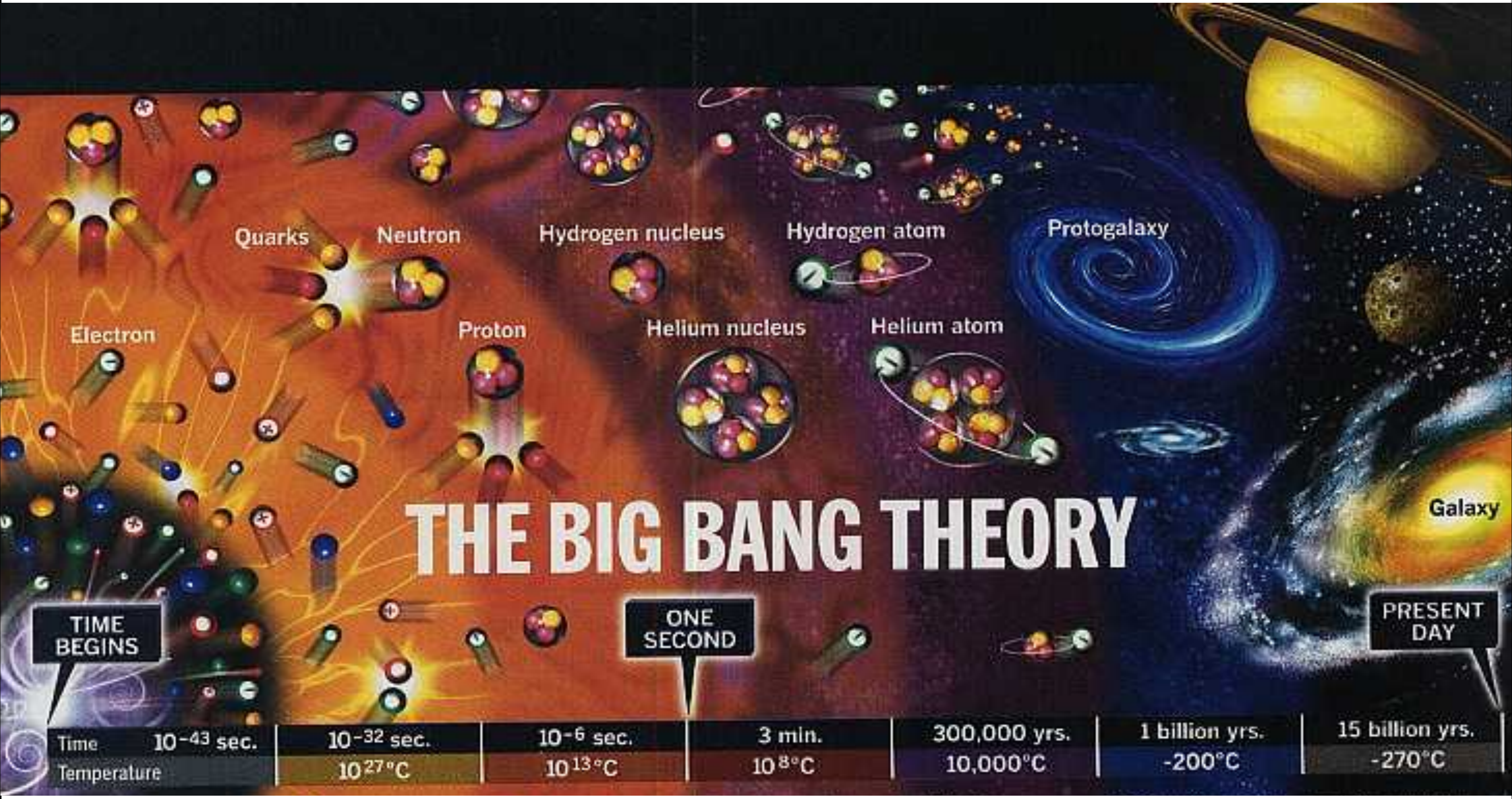
TUM LMU Excellence Cluster Universe

Technische Universität München

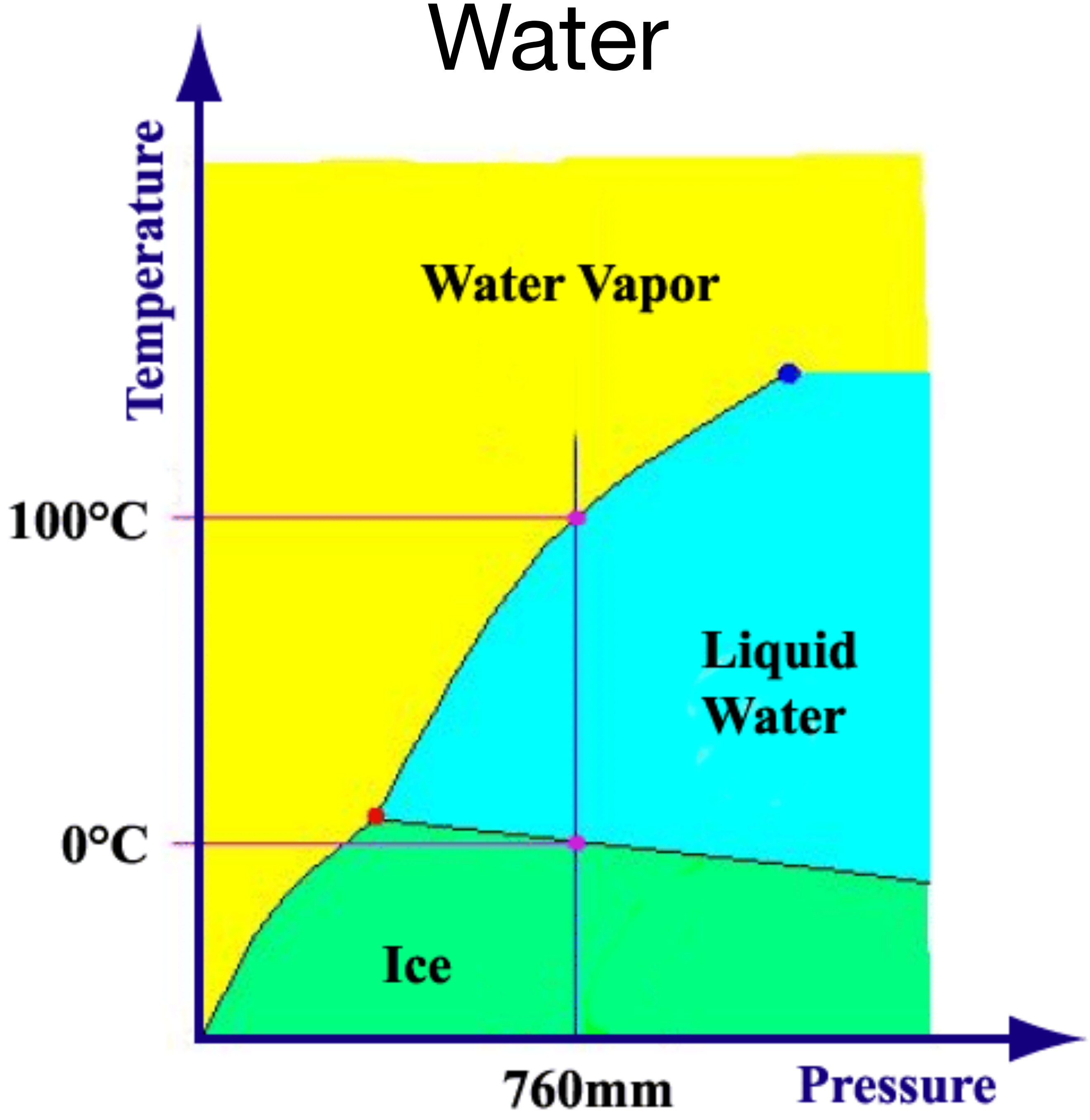
Introduction

The History of the Universe

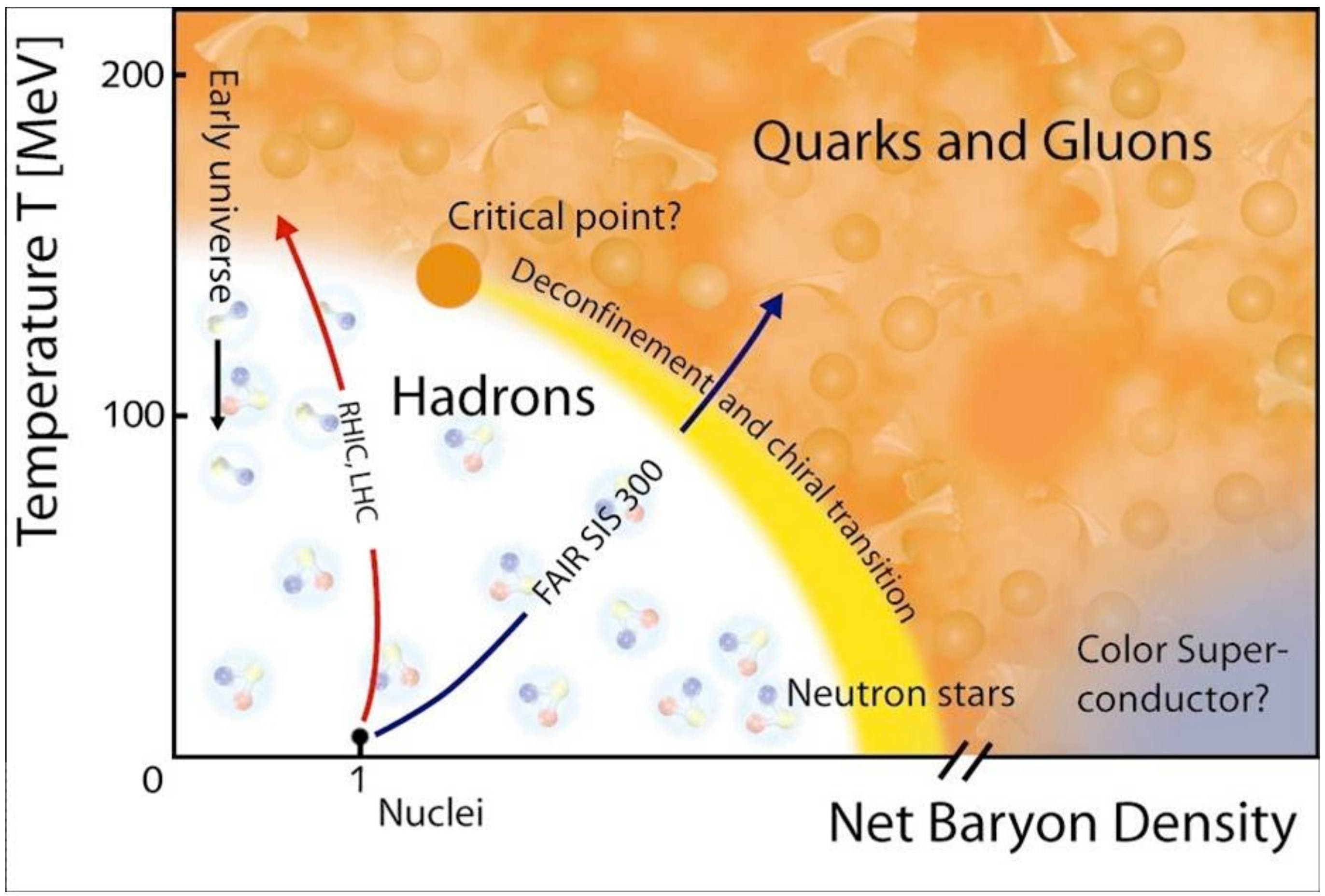


Phases of Matter

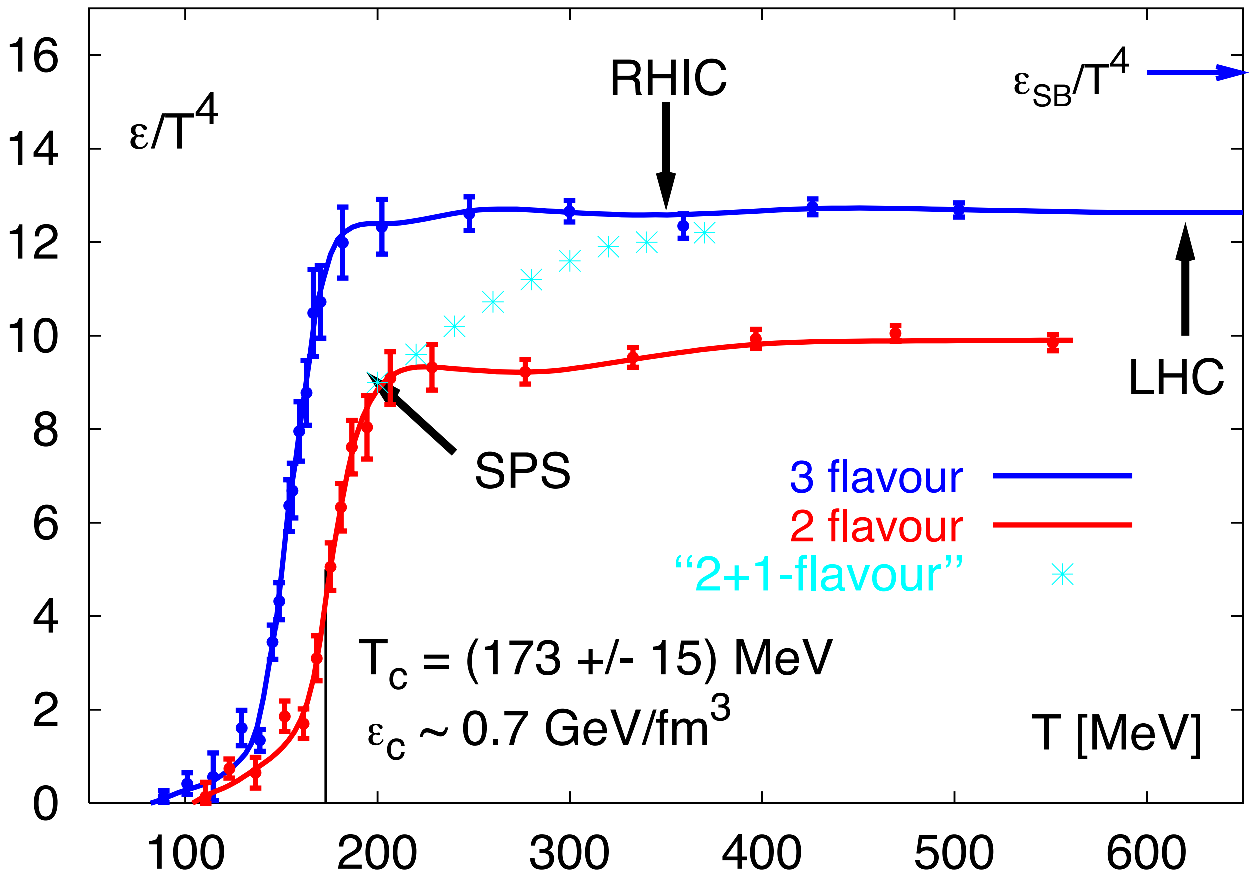
Water

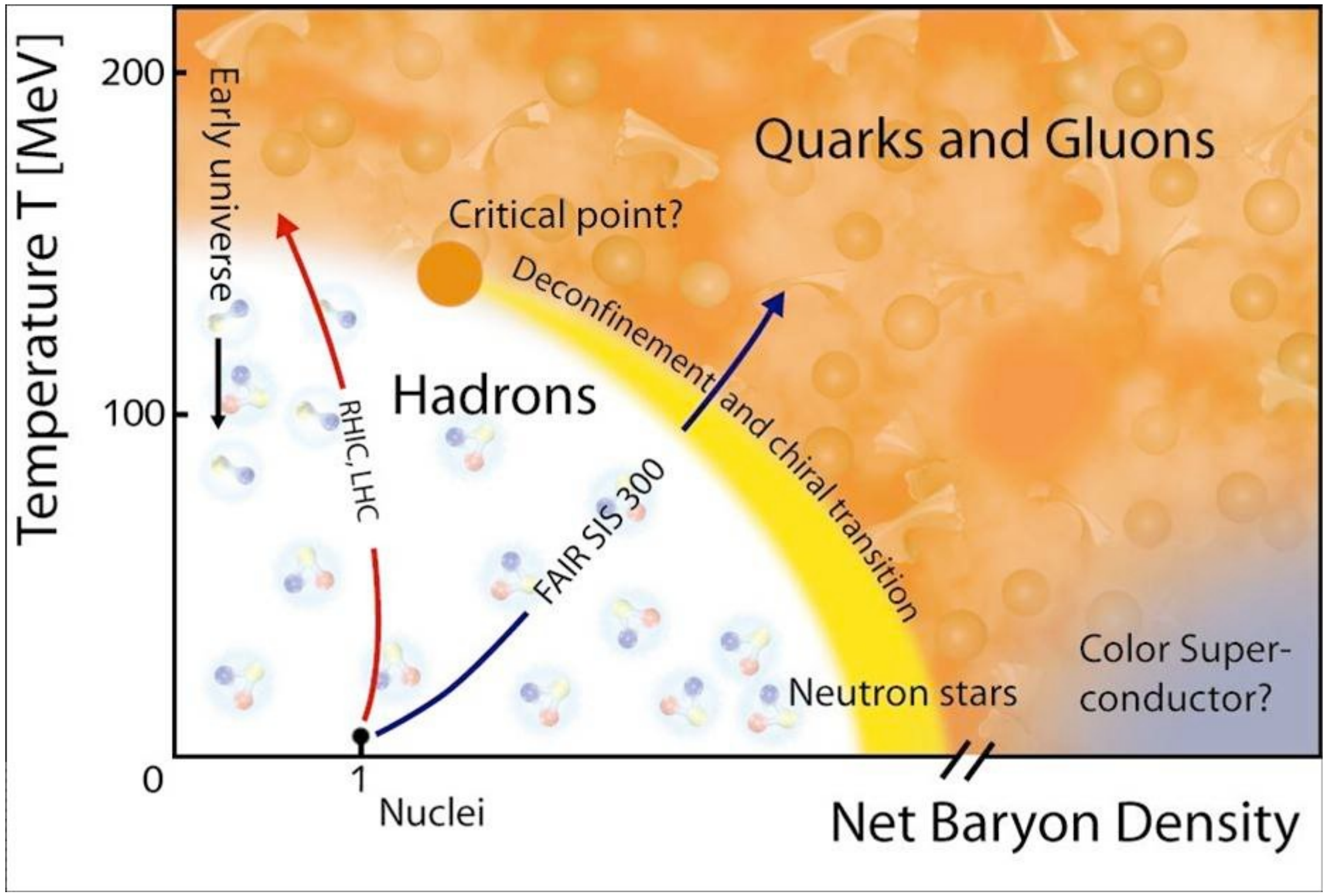


QCD Matter



Phases of QCD Matter

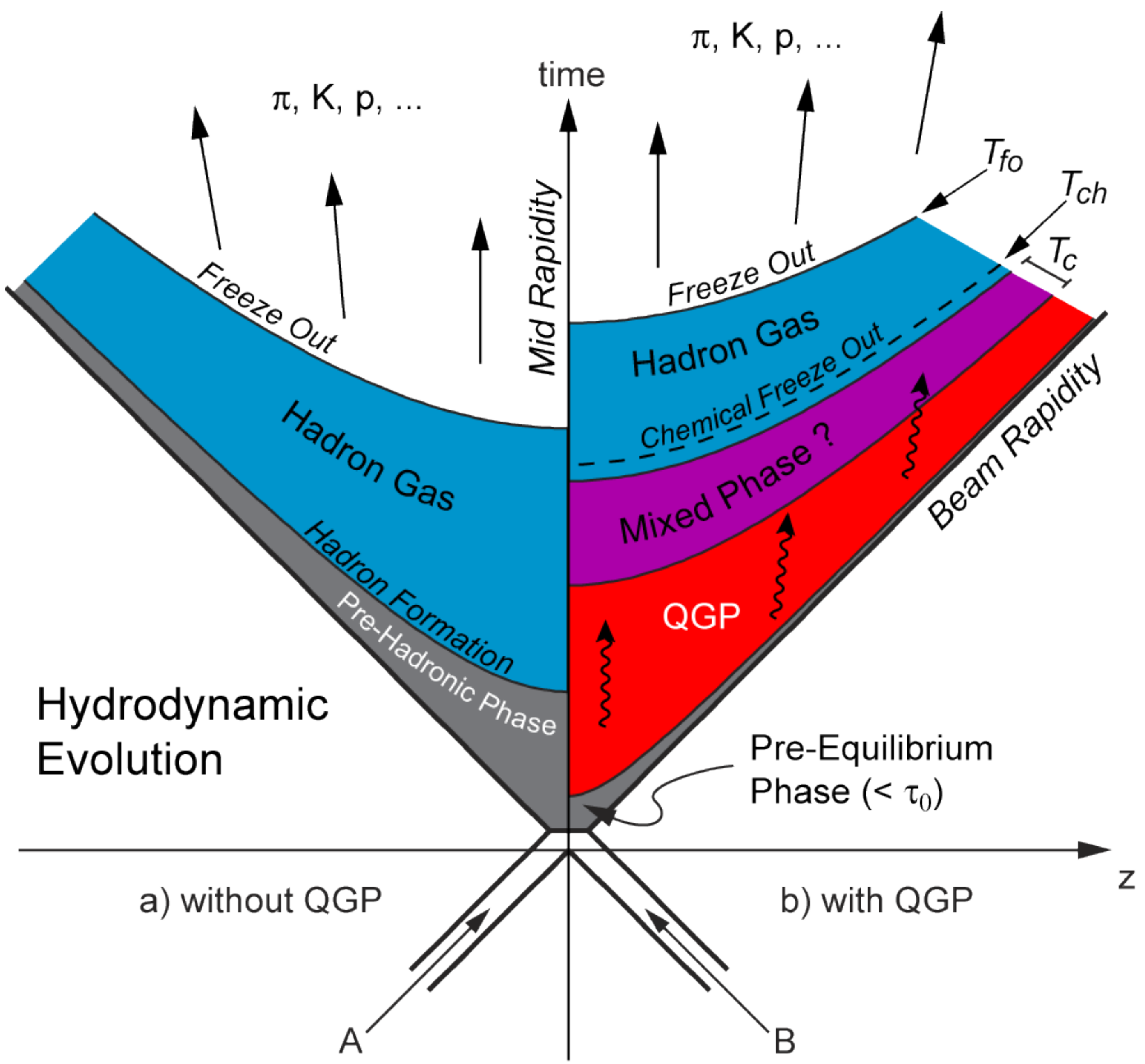


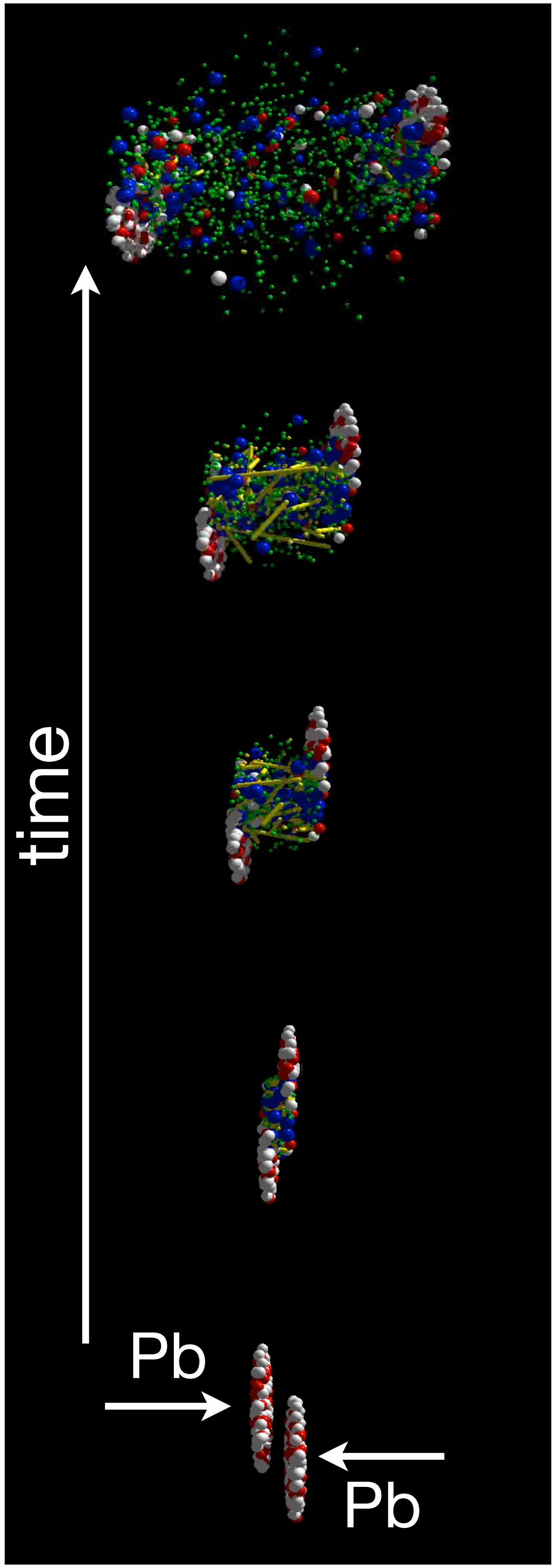


- Phase transition at T_c =170 MeV
  - 1 MeV ~ 10^{10} K → $T_c = 2\times10^{12}$ K
- Centre of the sun: 2×10^7 K
- The QGP is more than 100 000 times hotter than the centre of the sun

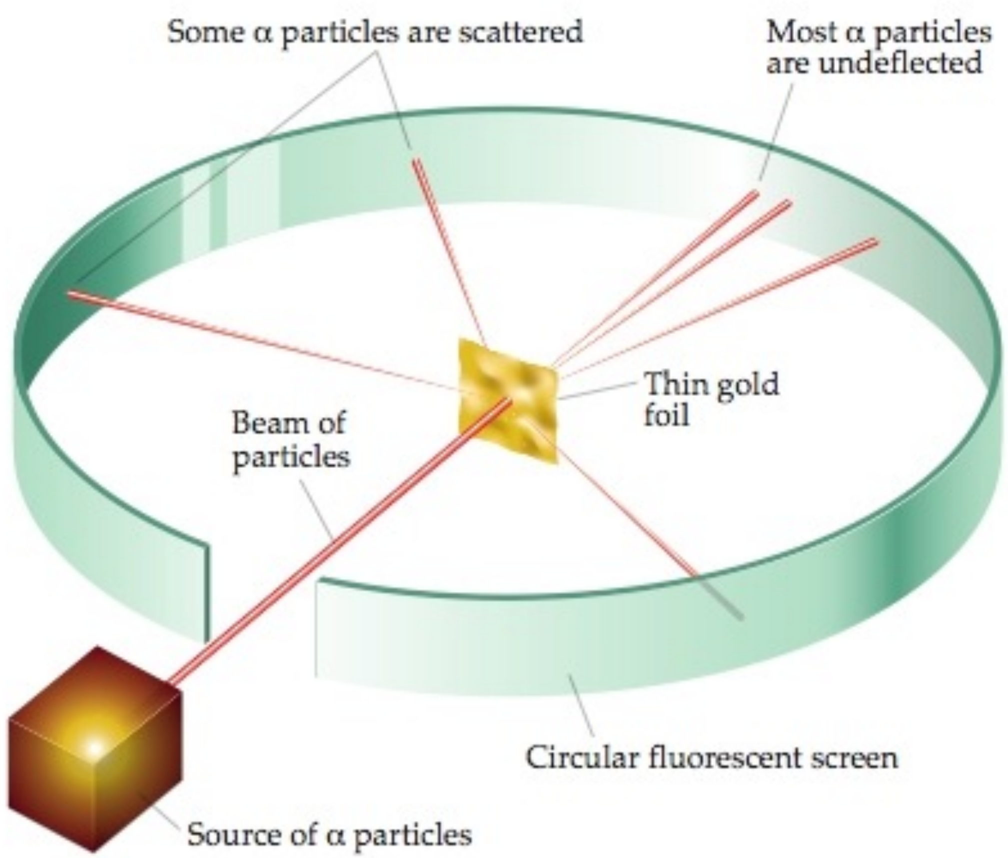
Creating the QGP: Heavy Ion Collisions

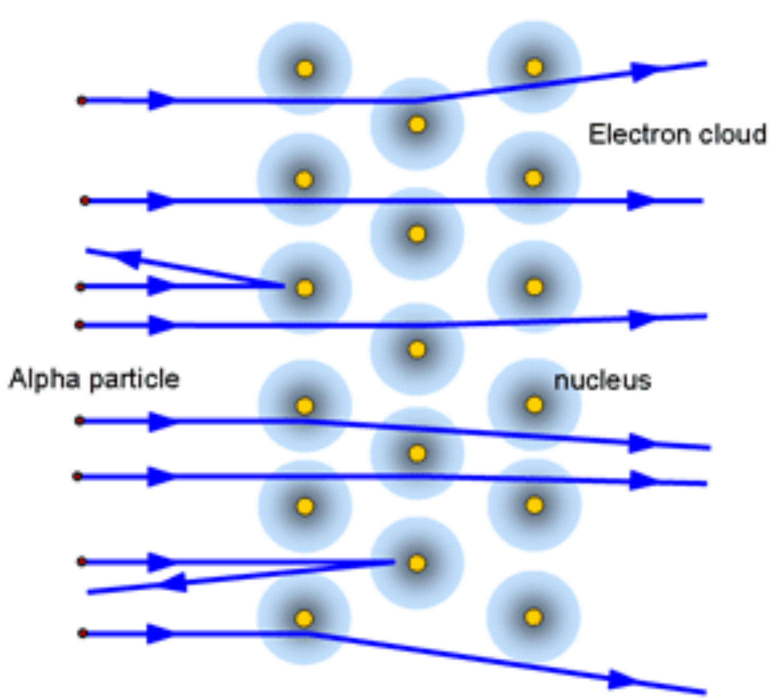
- Quark-gluon plasma (QGP) existed in the early universe:
  - conditions: extremely hot and high energy density
- To (re)create a QGP:
  - put a lot of nucleons with high energy in a small space
    → Heavy-Ion Collisions at ultra-relativistic energies



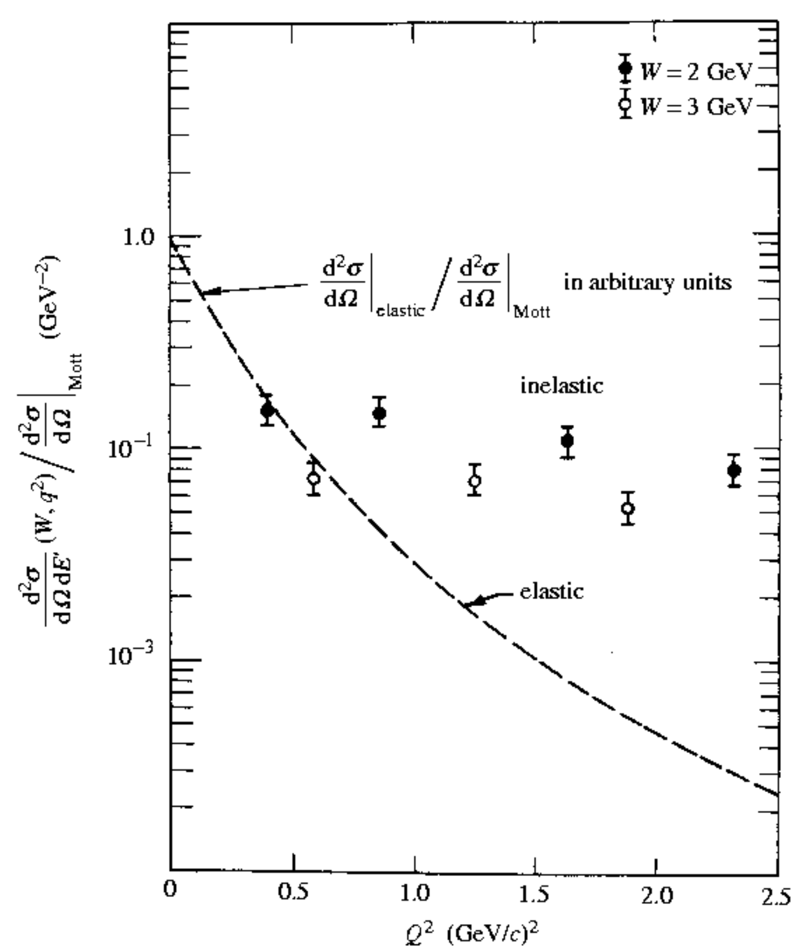


How to Probe the Structure of Matter?

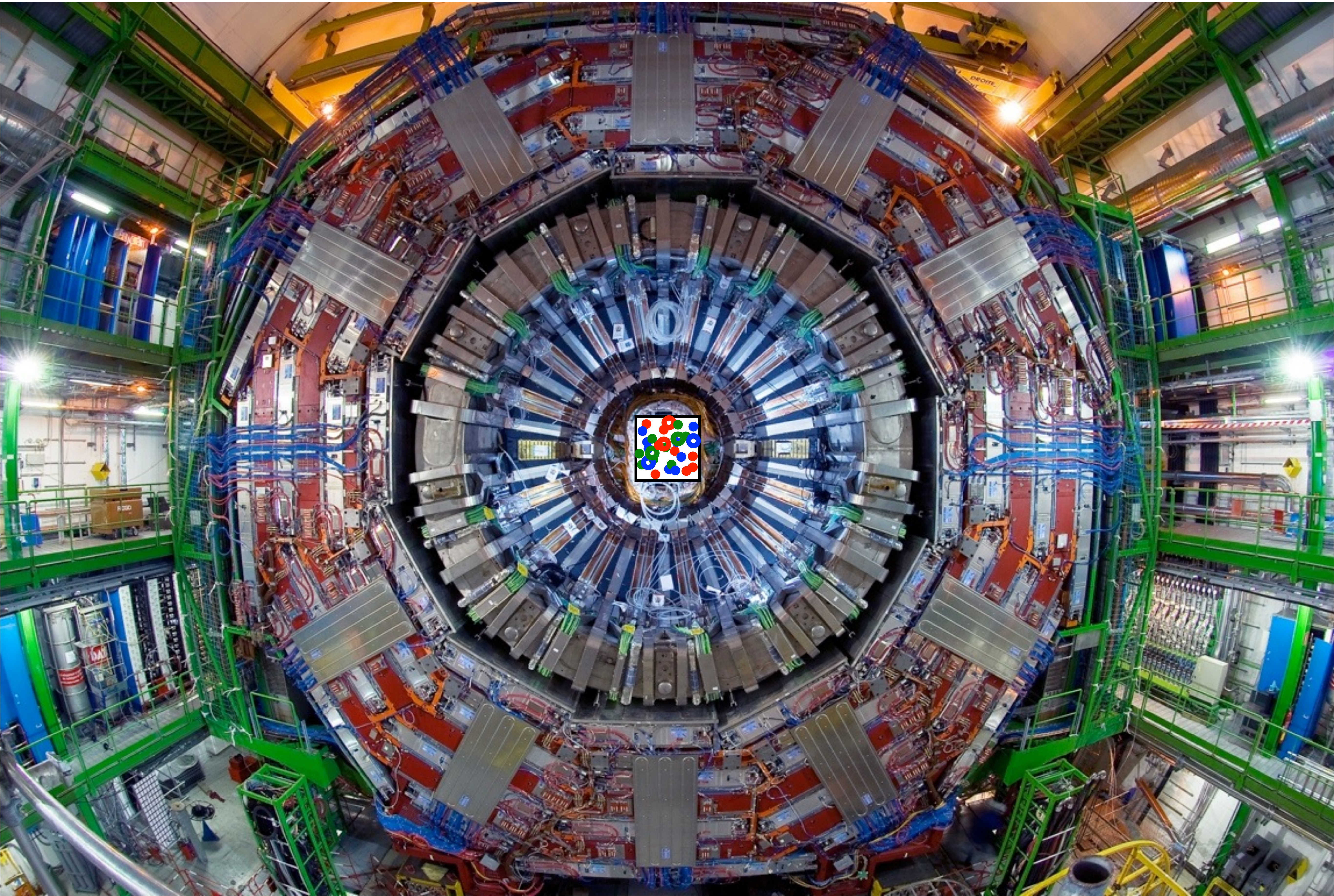




- Rutherford experiment:
  - α → atom: discovery of the nucleus
  - elastic collisions
- SLAC electron scattering:
  - e → proton: discovery of quarks
  - inelastic collisions



Rutherford Experiment on a QGP?



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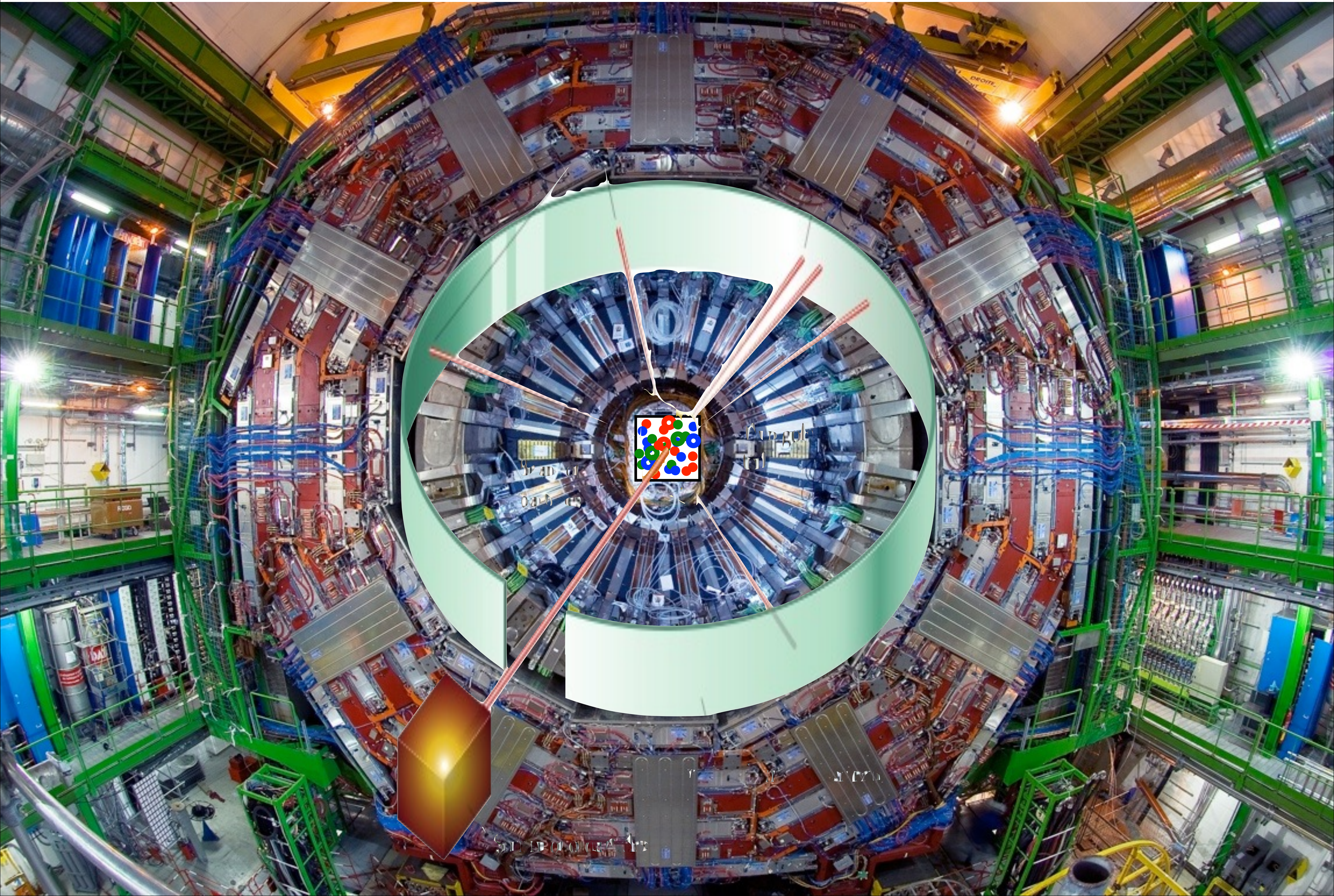
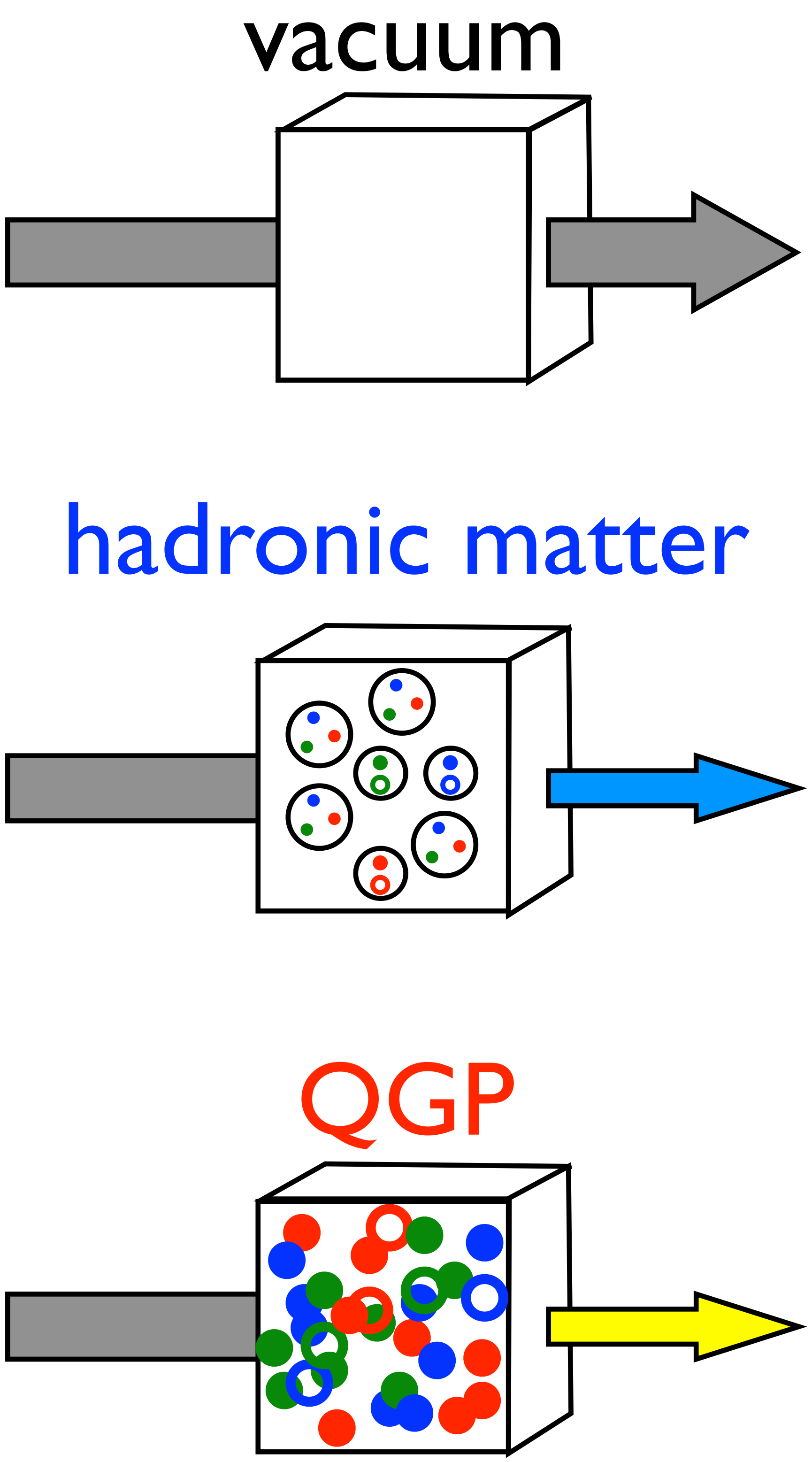
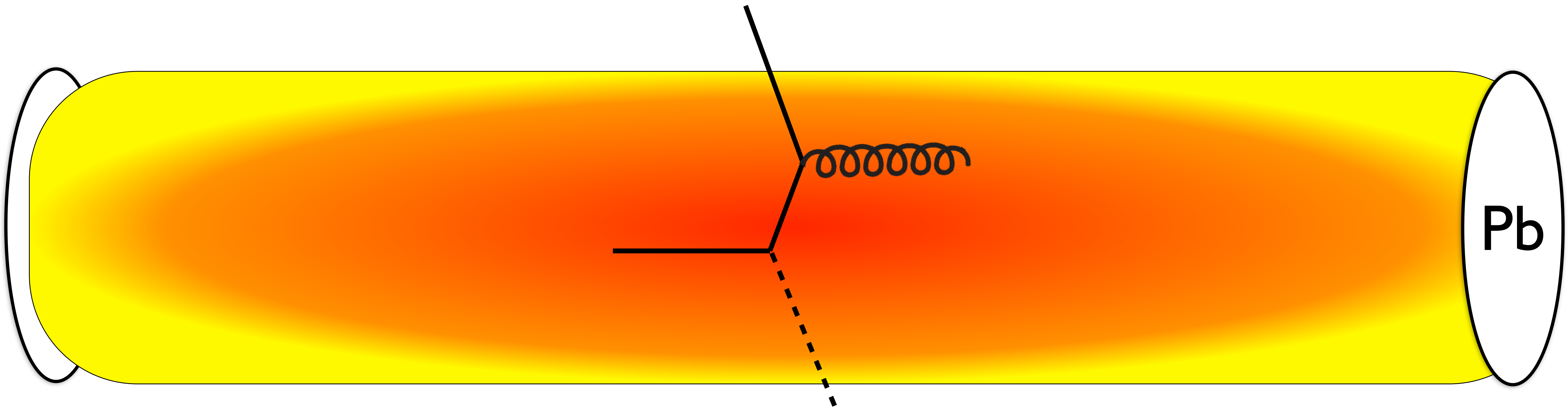


How to Probe the QGP?



- Has to be well understood in pp collisions
- Effect of hadronic matter has to be understood and accounted for
- Has to be strongly affected by the QGP

Hard Probes of the QGP



- Create the probes as part of the collision
- Create probes before the QGP forms
- Control probes not affected by the QGP to calibrate measurements
- Collisions without QGP to test cold nuclear matter effects
    - pp collisions, p-nucleus collisions, light-ion collisions

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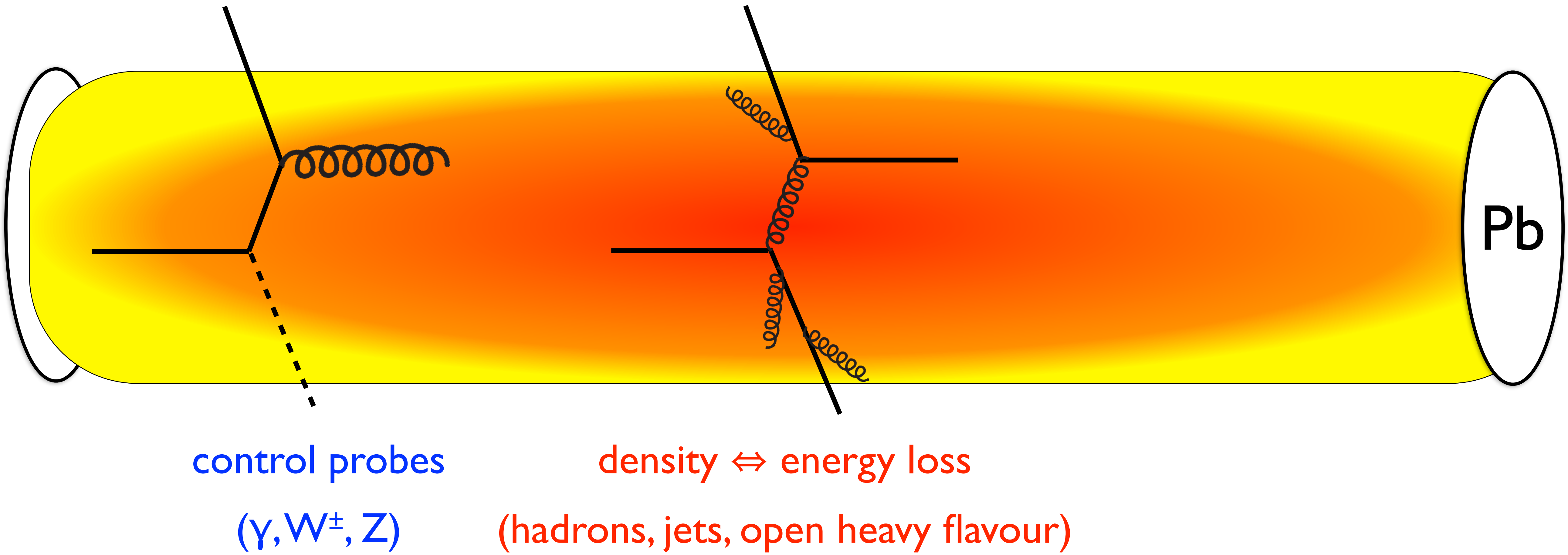

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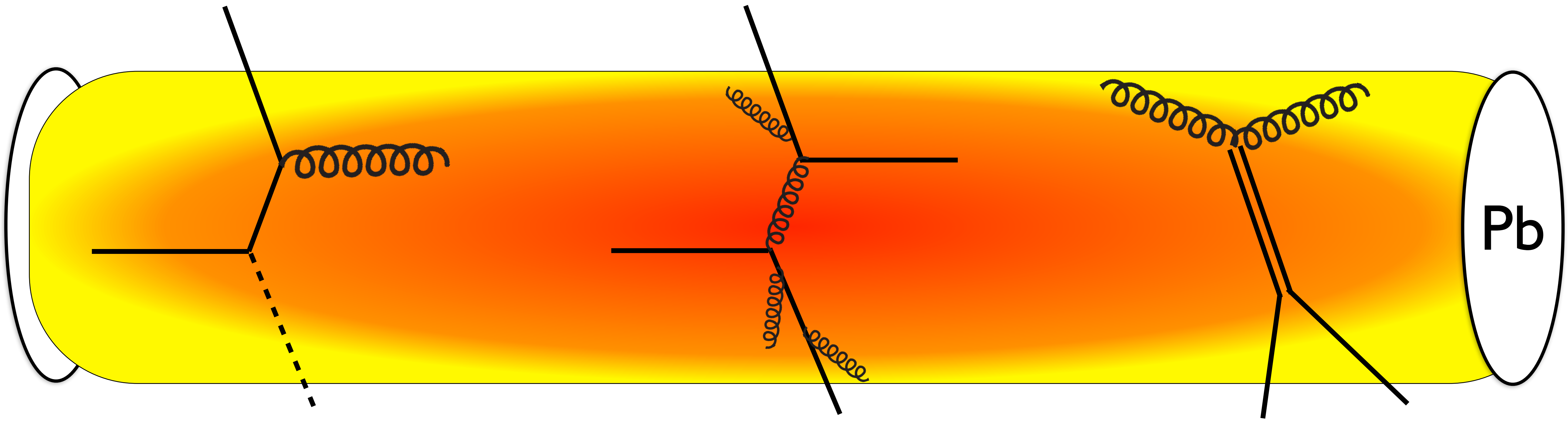

control probes
(γ, $W^{\pm}$, Z)

density ⇔ energy loss
(hadrons, jets, open heavy flavour)

temperature ⇔ dissociation
(quarkonia)

- Create the probes as part of the collision
- Create probes before the QGP forms
- Control probes not affected by the QGP to calibrate measurements
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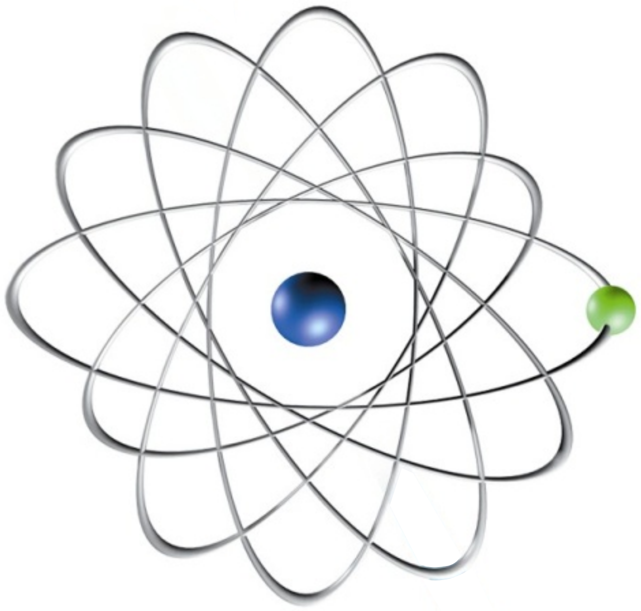
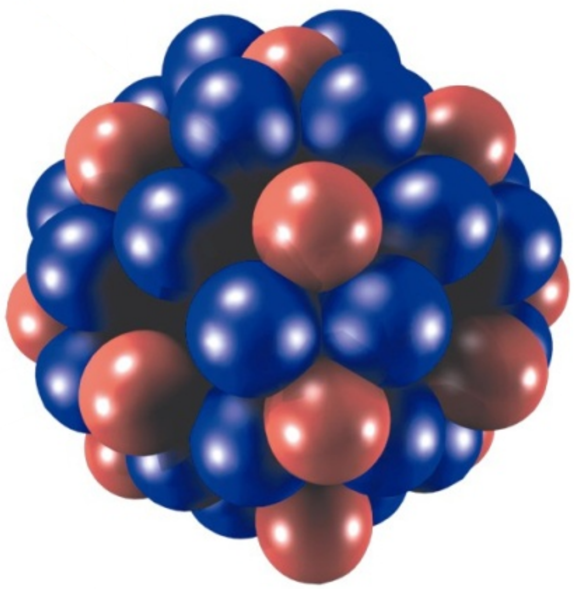
The Mass of Composite Systems

Atom:
10^{-10} m



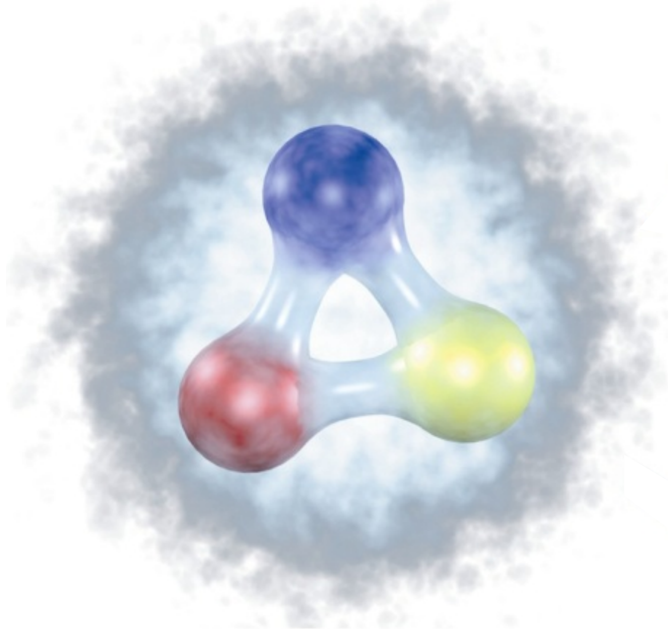
$M \approx \Sigma m_i$
binding energy
effect $\approx 10^{-8}$

Nucleus:
10^{-14} m



$M \approx \Sigma m_i$
binding energy
effect $\approx 10^{-3}$

Nucleon:
10^{-15} m



$M \gg \Sigma m_i$
mass given by energy stored in motion of quarks and by energy in colour gluon fields

- Role of chiral symmetry breaking
  - Chiral symmetry = fundamental symmetry of QCD for massless quarks
  - Chiral symmetry broken on hadron level

Chirality

- Chirality (from the greek word for hand: "χειρ")
  - when an object differs from its mirror image
- Simplification of chirality: helicity
  (projection of a particle's spin on its momentum direction)
- Massive particles P
  - left and right handed components must exist
  - $m > 0$ particle moves with $v < c$
    - P looks left handed in the laboratory
    - P will look right handed in a rest frame moving faster than P but in the same direction
  - chirality is NOT a conserved quantity
- In a massless world
  - chirality is conserved
  - careful: $m = 0$ is a sufficient but not a necessary condition

QCD and Chiral Symmetry Breaking

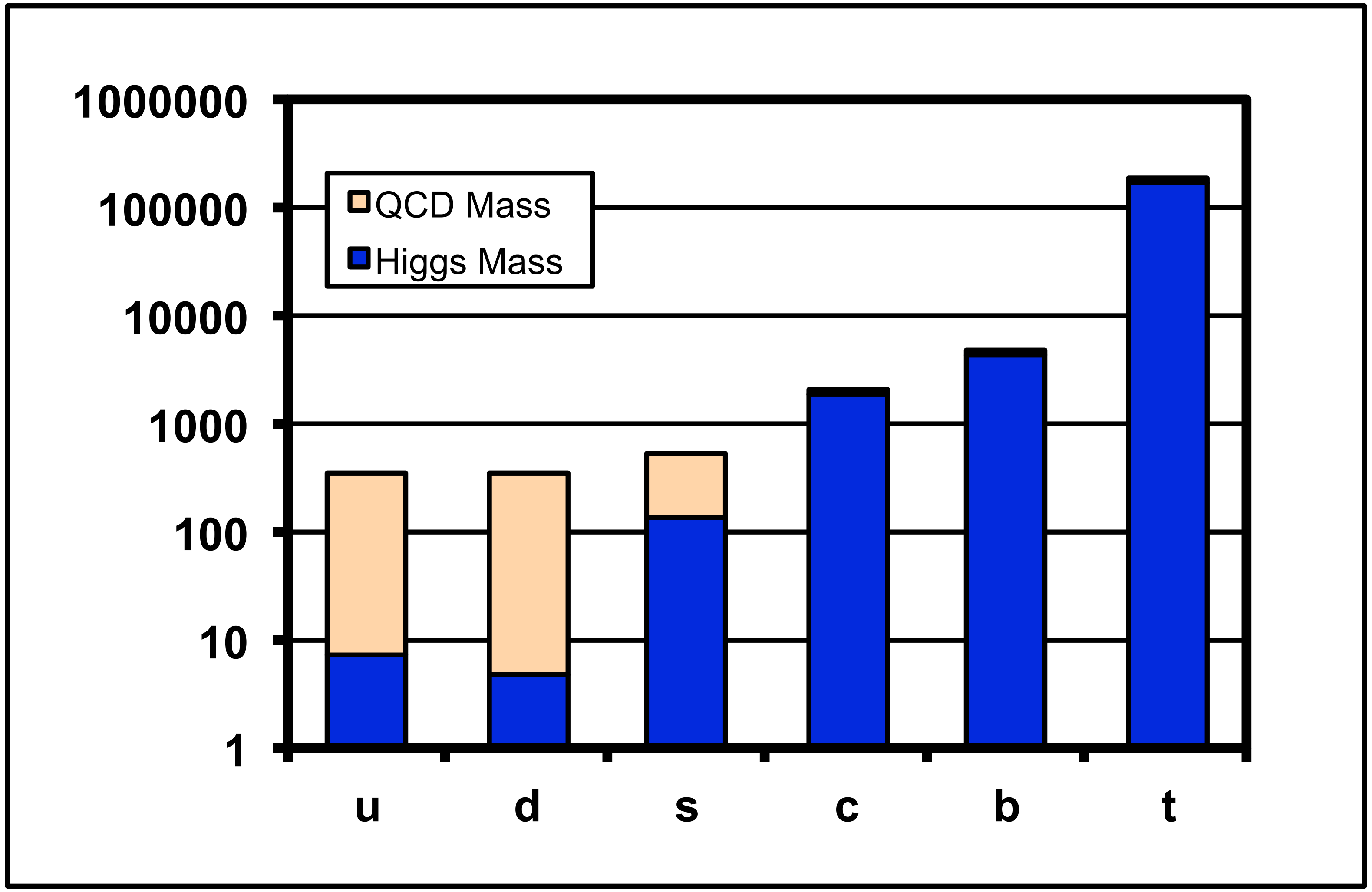
- The QCD Lagrangian:

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - \mathcal{M}_q)q - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \quad , \qquad D_\mu = \partial_\mu + ig_s\frac{\lambda_a}{2}A^a_\mu \ ,$$

- Explicit chiral symmetry breaking
  - mass term $\bar{q}\ M_q\ q$ in the QCD Lagrangian
- Chiral limit: $m_u = m_d = m_s = 0$
  - chirality would be conserved
  - all states have a ‘chiral partner’ (opposite parity and equal mass)

- Real life
  - a_1 ($J^P=1^+$) is chiral partner of ρ ($J^P=1^-$): $\Delta m \approx 500$ MeV
  - even worse for the nucleon: $N^*(½^-)$ and $N(½^+)$: $\Delta m \approx 600$ MeV
  - (small) current quark masses do not explain this
- Chiral symmetry is also spontaneously broken
  - spontaneously = dynamically

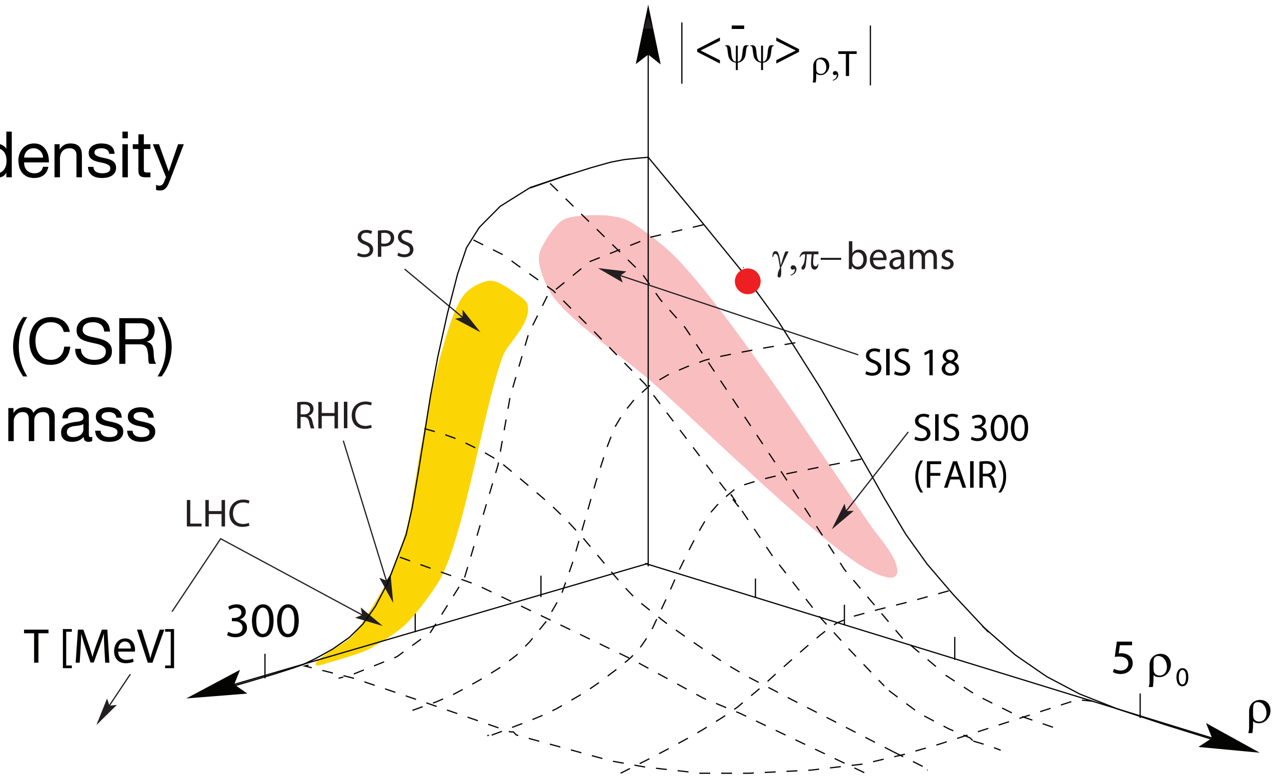
The Origin of Mass



- Current quark mass
  - generated by spontaneous symmetry breaking (Higgs mass)
  - contributes ~5% to the visible (our) mass
- Constituent quark mass
  - ~95% generated by spontaneous chiral symmetry breaking (QCD mass)

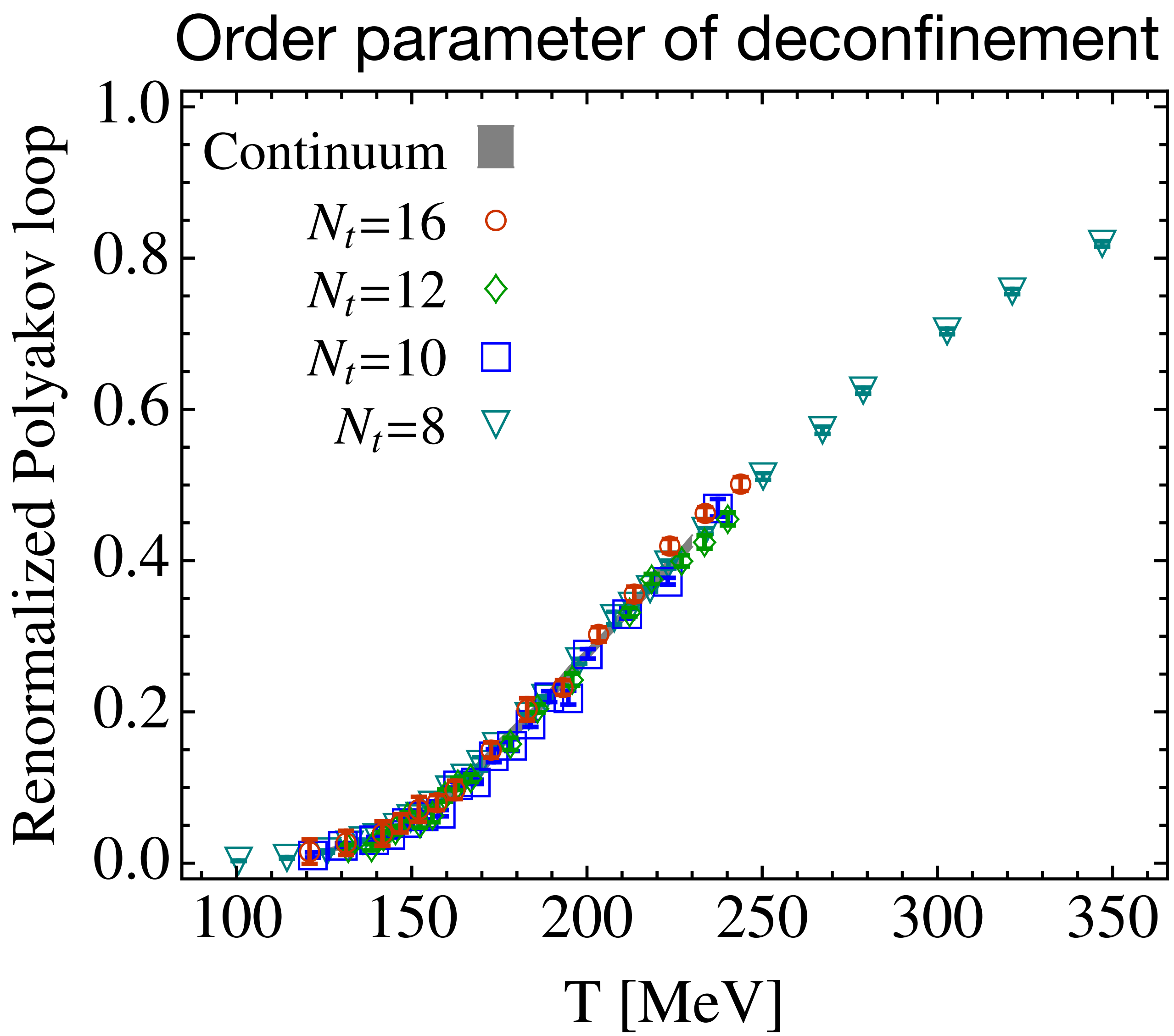
Chiral Symmetry Restoration

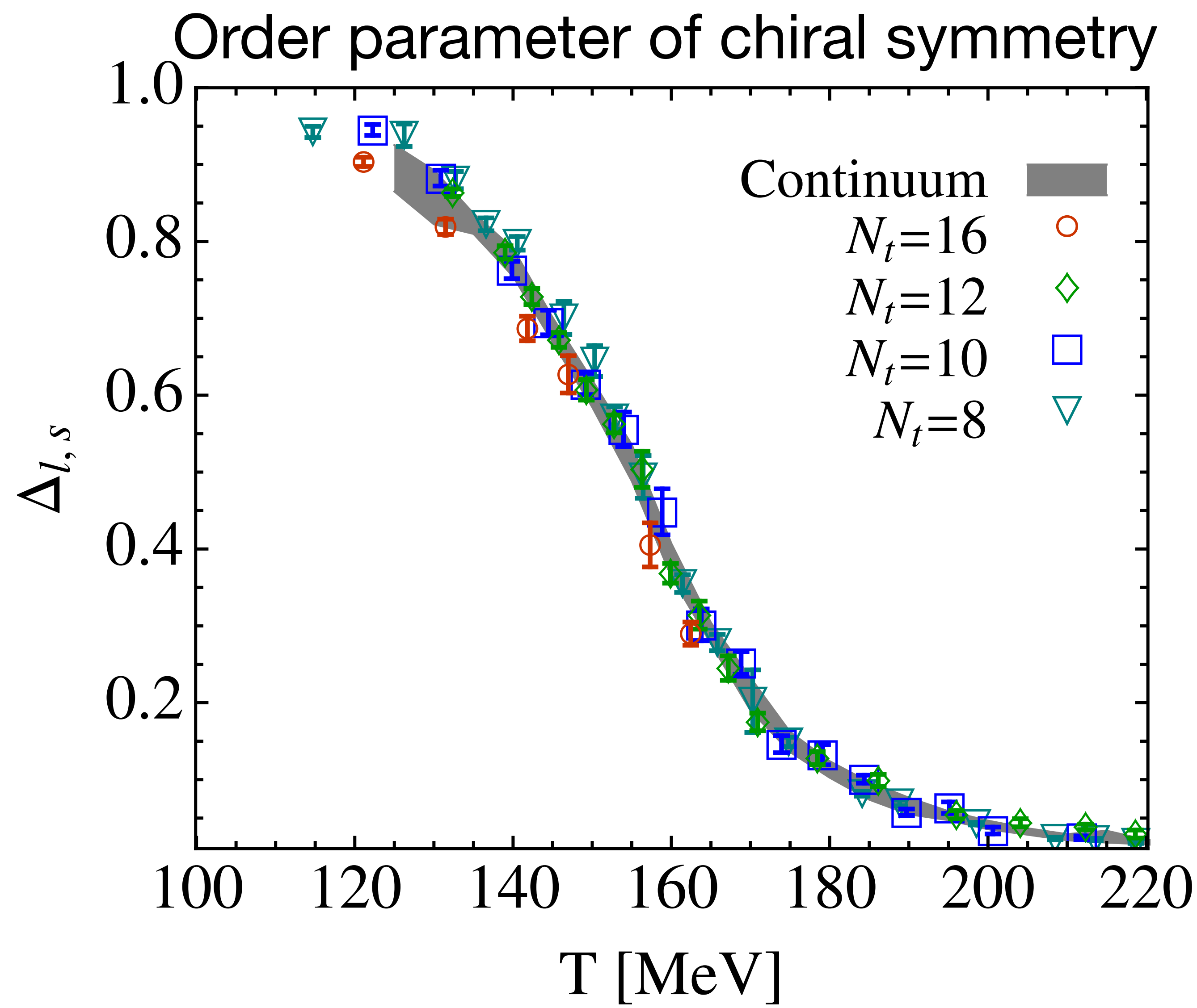
- Spontaneous symmetry breaking gives rise to a nonzero ‘order parameter’
  - QCD: quark condensate $\langle\bar{q}q\rangle \approx -250\ \mathrm{MeV}^3$
  - many models (!): hadron mass and quark condensate are linked
- Numerical QCD calculations
  - at high temperature and/or high baryon density
    → deconfinement and $\langle\bar{q}q\rangle \to 0$
  - approximate chiral symmetry restoration (CSR)
    → constituent mass approaches current mass
- Chiral Symmetry Restoration
  - expect modification of hadron
    spectral properties (mass m, width Γ)



- QCD Lagrangian → parity doublets are degenerate in mass

Chiral Phase Transition





Wuppertal-Budapest Collaboration,
JHEP 09 (2010) 073

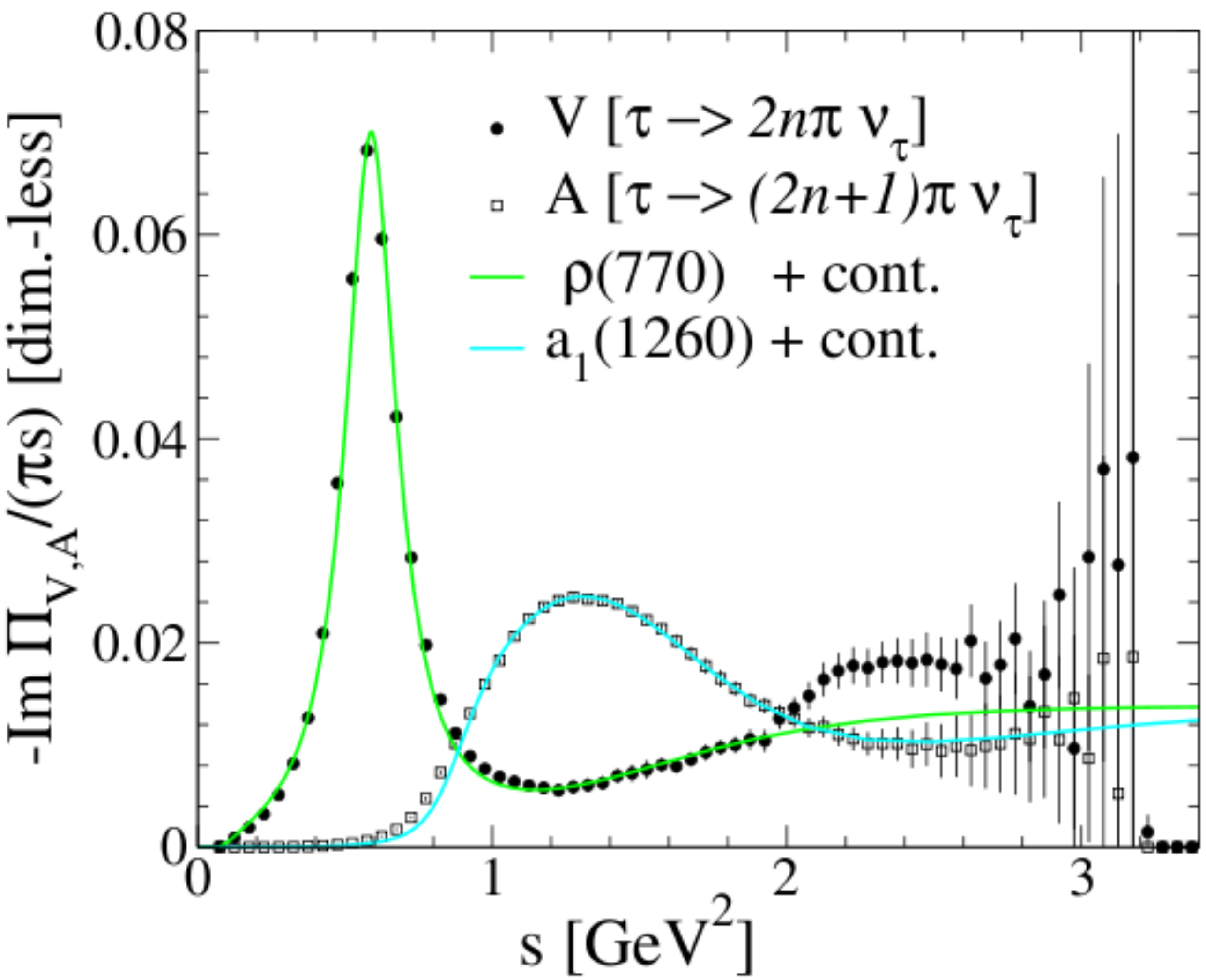
- Lattice QCD calculation
  - Predict chiral symmetry restoration already a T lower than deconfinement phase transitions

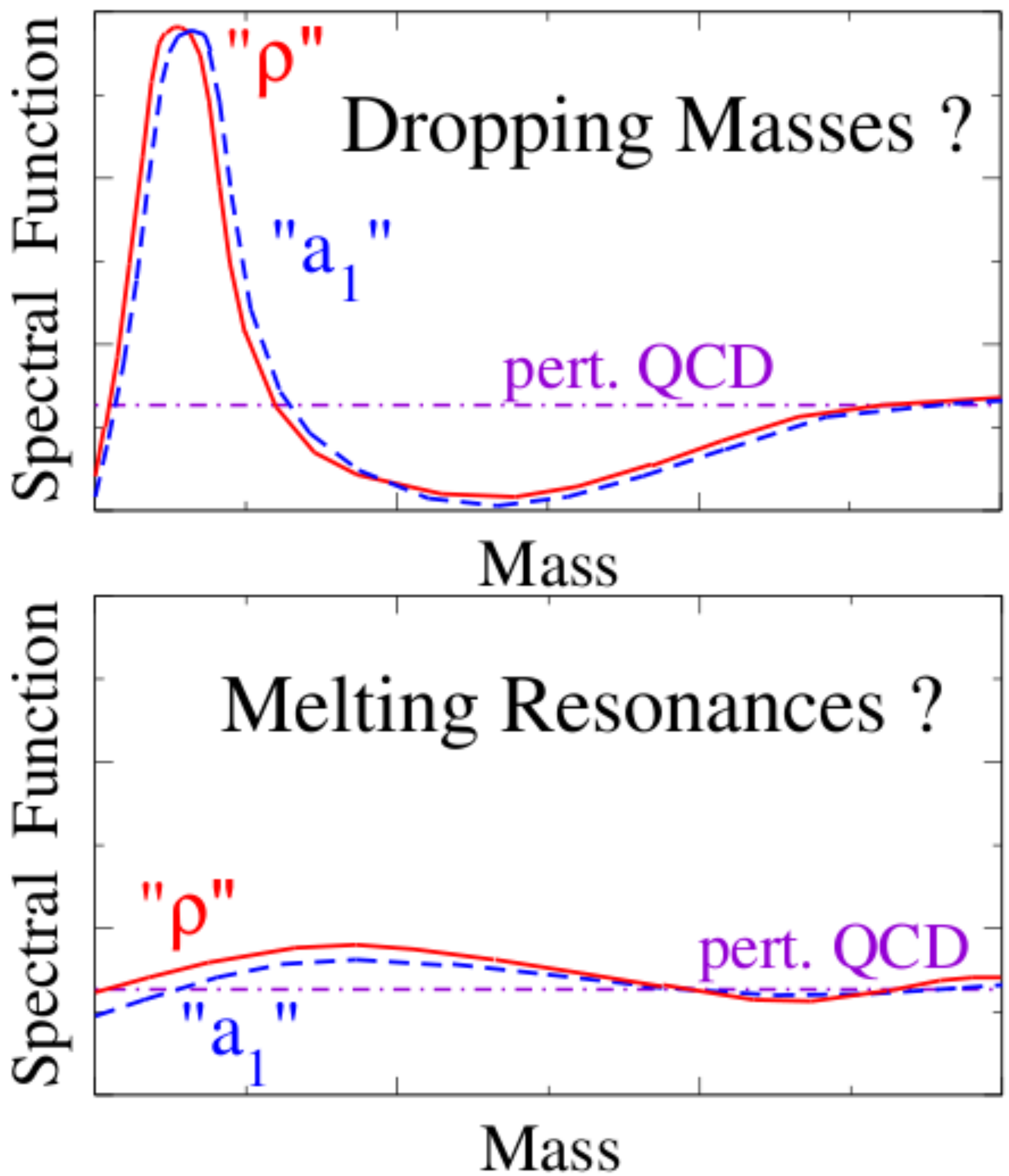
Chiral Symmetry Restoration (CSR)

- Brown-Rho scaling

G. Brown & M. Rho, PRL (1991) 2720

$$\frac{\langle\langle\bar{\psi}\psi\rangle\rangle}{\langle\bar{\psi}\psi\rangle} = \left(\frac{f_\pi^*}{f_\pi}\right)^3 \quad \text{and} \quad \frac{f_\pi^*}{f_\pi} = \frac{m_\sigma^*}{m_\sigma} = \frac{m_N^*}{m_N} = \frac{m_\rho^*}{m_\rho} = \frac{m_\omega^*}{m_\omega}$$



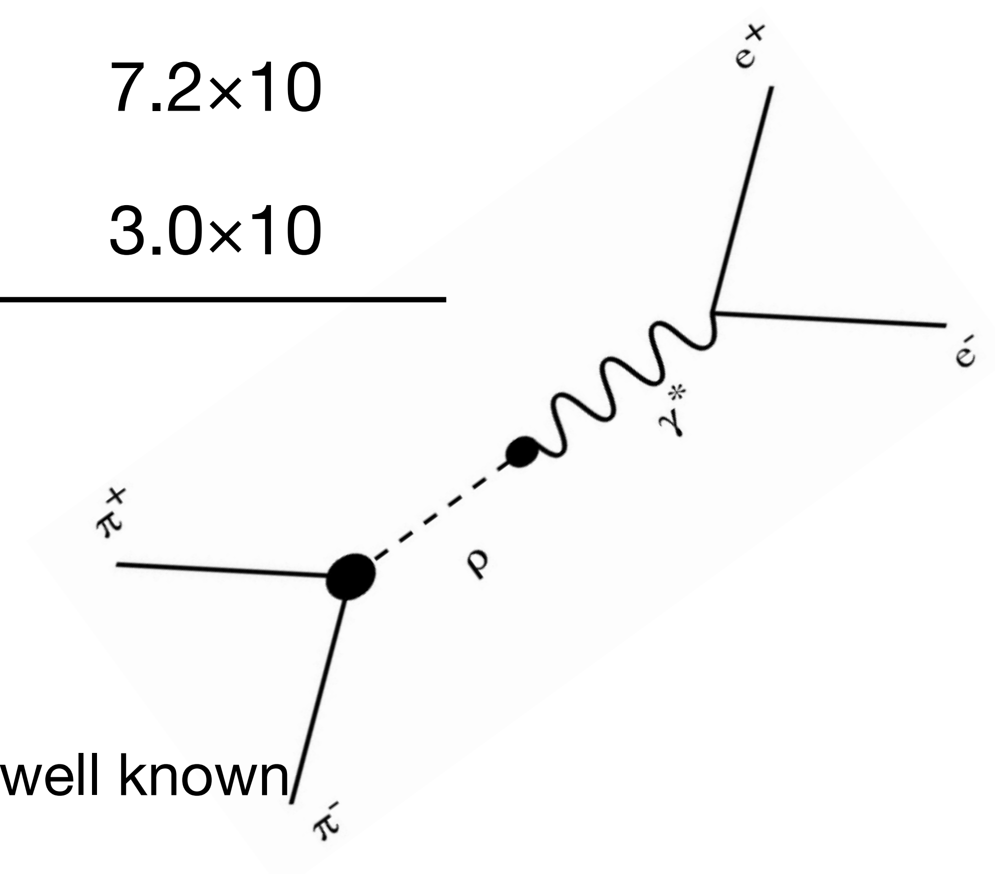


Best Probes for CSR?

- Requirement: carry hadron spectral properties from (T, ρ_B) to detectors
  - relate to hadrons in medium
  - leave medium without final state interaction
- Dileptons from vector meson decays:

	m [MeV/c	Γ	τ [fm/c]	BR→ee
ρ	770	150	1.3	4.7×10
ω	782	8.6	23	7.2×10
ϕ	1020	4.4	44	3.0×10

  - best candidate: ρ meson
    - short lived (compare to τ_{QGP} = 10 fm/c)
    - decay (and regeneration) in medium
    - properties of in-medium ρ and of medium itself not well known



Dilepton production

- Emission rate of dileptons per volume

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

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

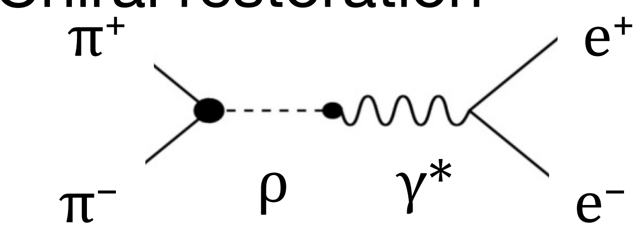
$$L(M) = \sqrt{1-\frac{m_l^2}{M^2}}\left(1+\frac{2m_l^2}{M^2}\right)$$

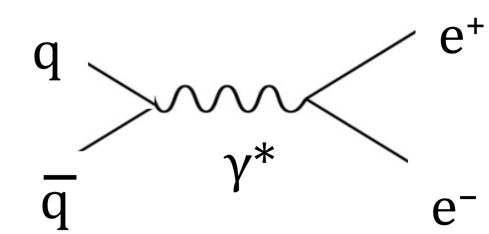
$\gamma^* \to e^+e^-$ decay — EM correlator, medium property — Boltzmann factor, temperature

Hadronic contribution
Vector Meson Dominance → Medium modification of meson, Chiral restoration

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}^2\right)\mathrm{Im}D_V(M) \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q^2) \end{cases}$$

$q\bar{q}$ annihilation → Thermal radiation from partonic phase (QGP)



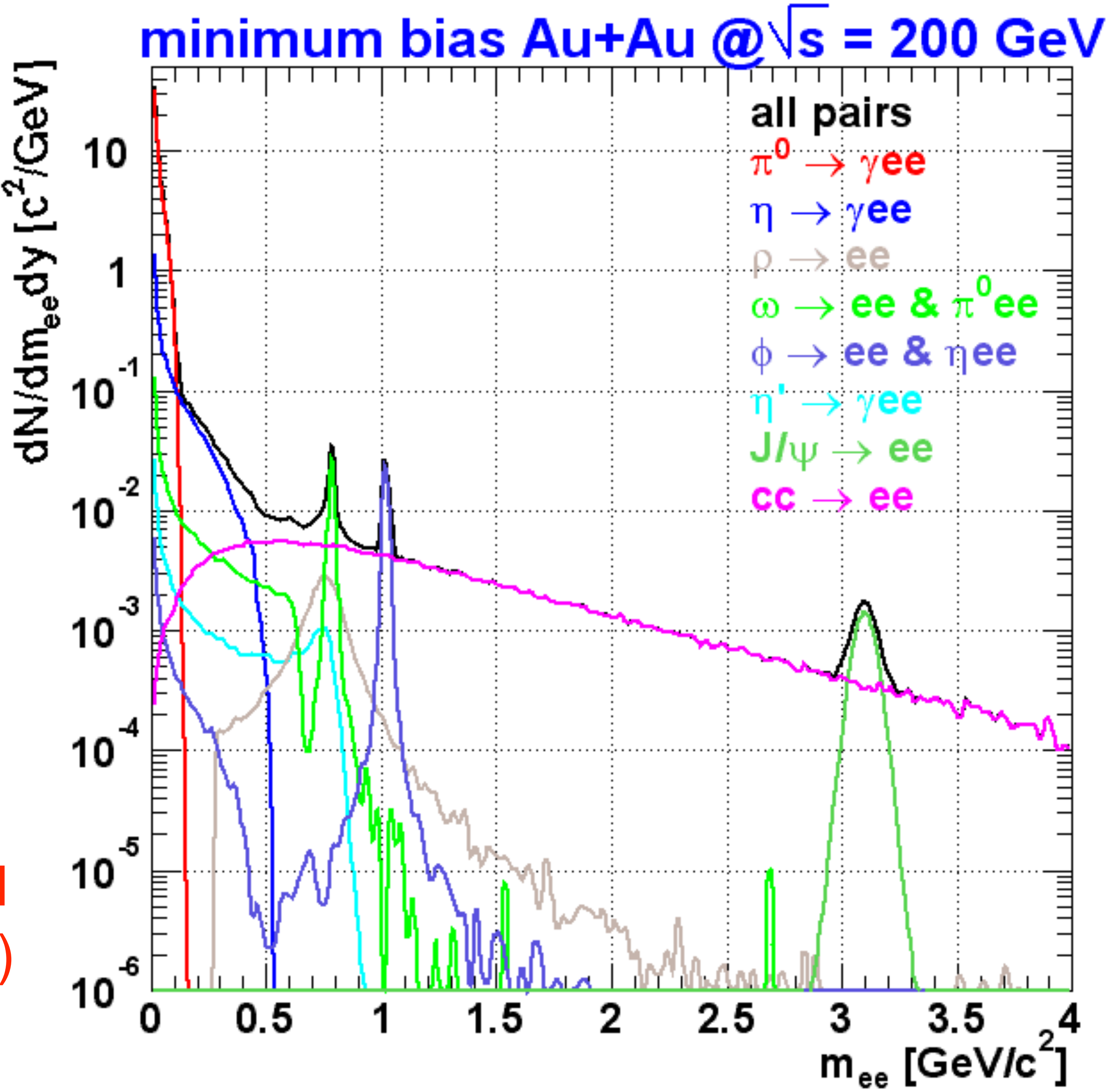


Thermal radiation from partonic phase (QGP)

- From emission rate of dileptons one can decode
  - medium effect on the EM correlator
  - temperature of the medium

Properties of the QGP

- What is its temperature?
  - measure thermal photons
- Does it restore chiral symmetry?
  - modification of the vector mesons
- How does it affect heavy quarks?
  - modification of the intermediate mass region
- All these questions can be answered by measuring dileptons (e^+e^- or $\mu^+\mu^-$)
  - no strong final state interactions:
    - leave collision system unperturbed
    - emitted at all stages: need to disentangle contributions



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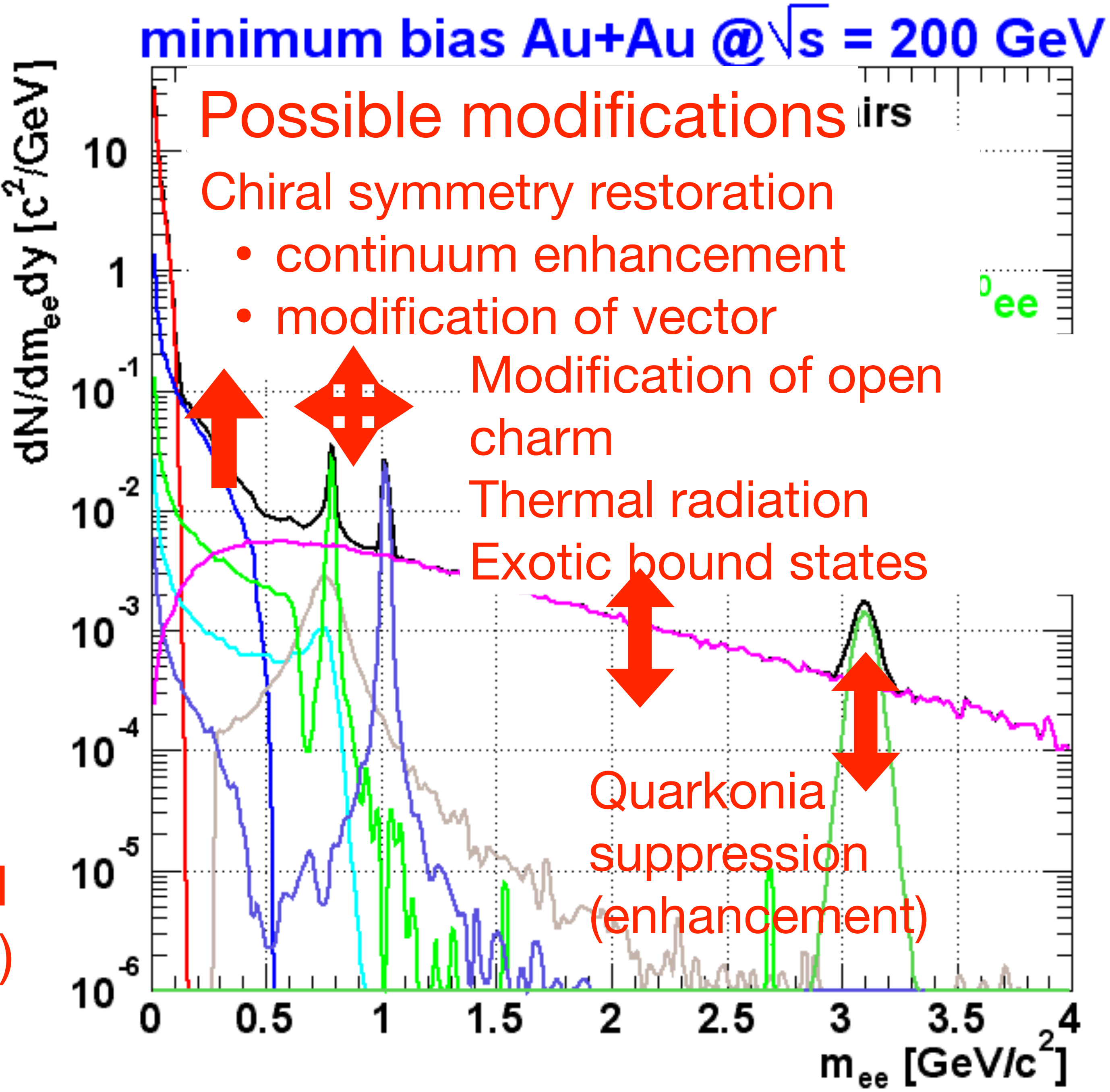
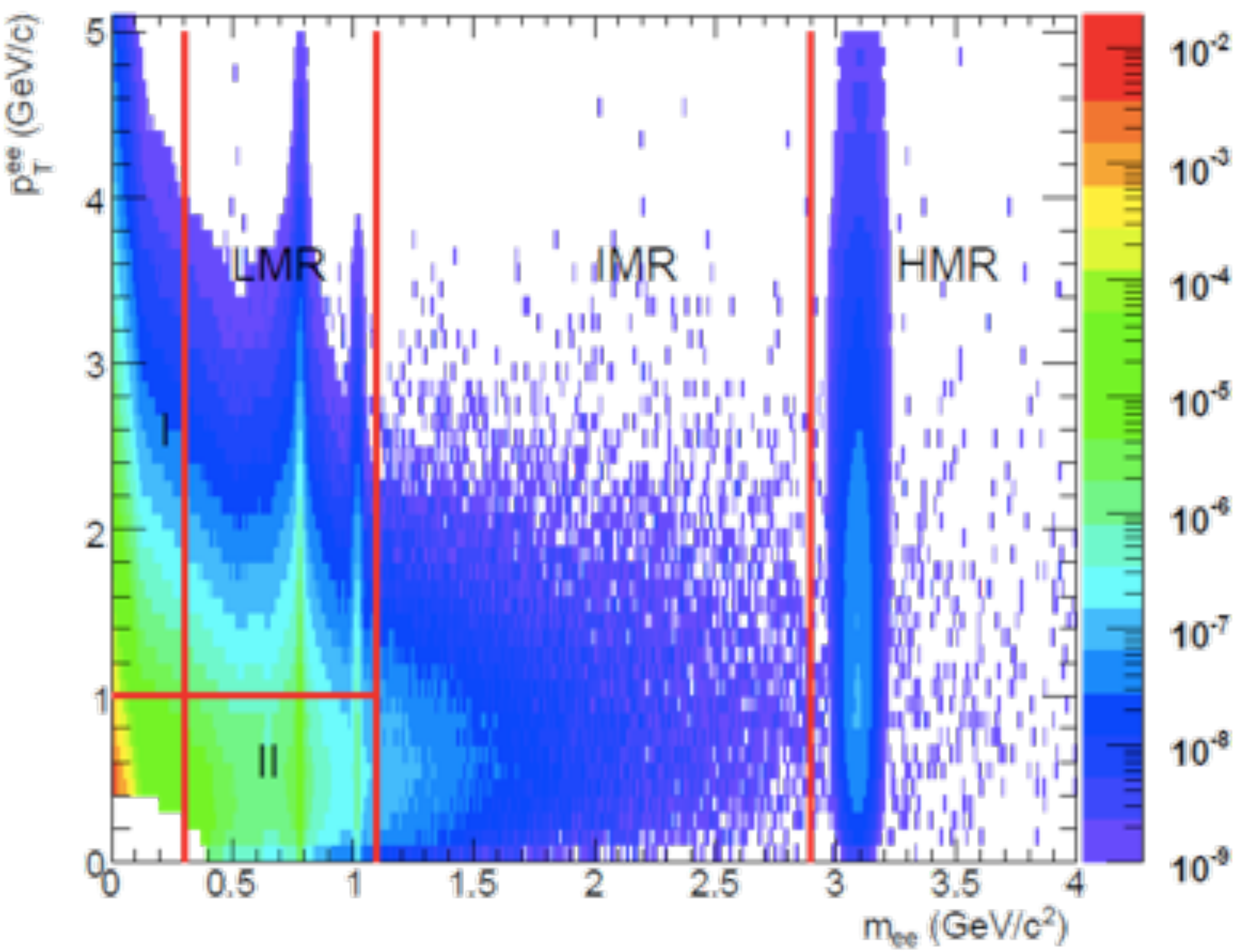


Dilepton Signals: p_T vs. mass

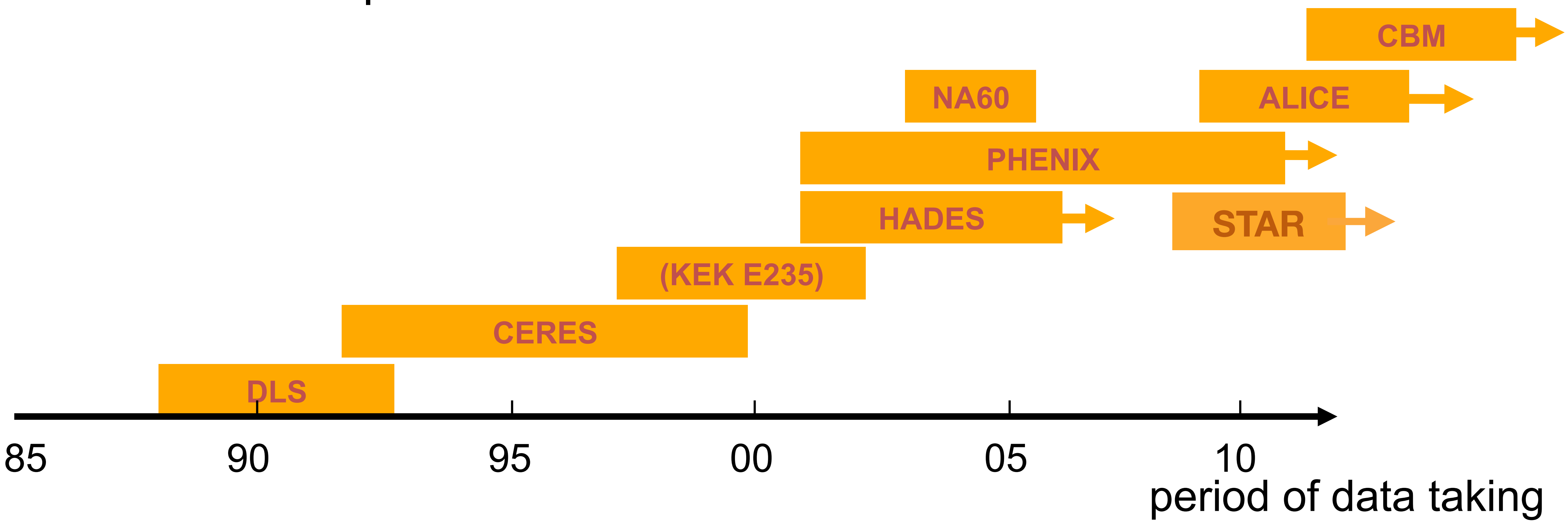


- LMR: $m_{ee} < 1.2$ GeV/c²
  - LMR I ($p_T \gg$ mee)
    quasi-real virtual photon region. Low mass pairs produced by higher order QED correction to the real photon emission
  - LMR II ($p_T < 1$ GeV)
    Enhancement of dileptons discovered at SPS (CERES, NA60)

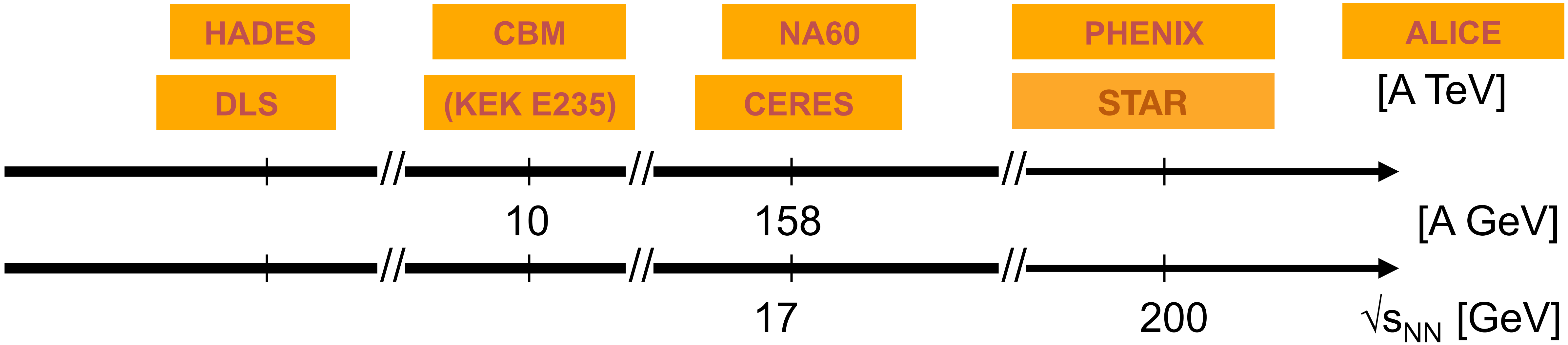
- Low Mass Region: $m_{ee} < 1.2$ GeV/c²
  - Dalitz decays of pseudo-scalar mesons
  - Direct decays of vector mesons
  - In-medium decay of ρ mesons in the hadronic gas phase
- Intermediate Mass Region:$1.2 < m_{ee} < 2.9$ GeV/c²
  - correlated semi-leptonic decays of charm quark pairs
  - Dileptons from the QGP
- High Mass Region: $m_{ee} > 2.9$ GeV/c²
  - Dileptons from hard processes
    - Drell-Yan process
    - correlated semi-leptonic decays of heavy quark pairs
    - Charmonium
    - Upsilon
  - HMR probe the initial stage
    - Little contribution from thermal radiation

HIN Low-mass Dilepton Experiments

- Time scale of experiments



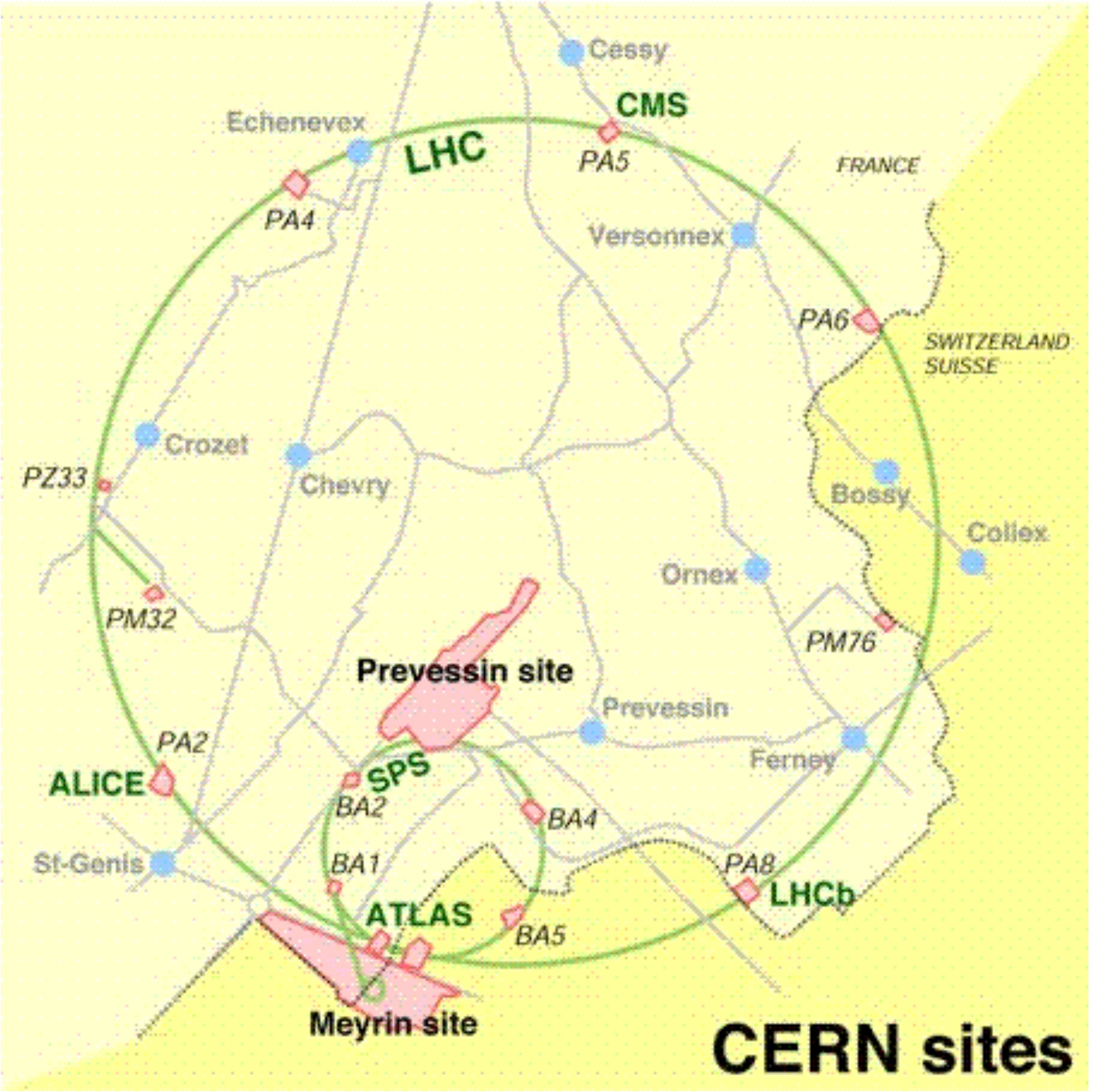
- Energy scale of experiments



SPS

The SPS at CERN

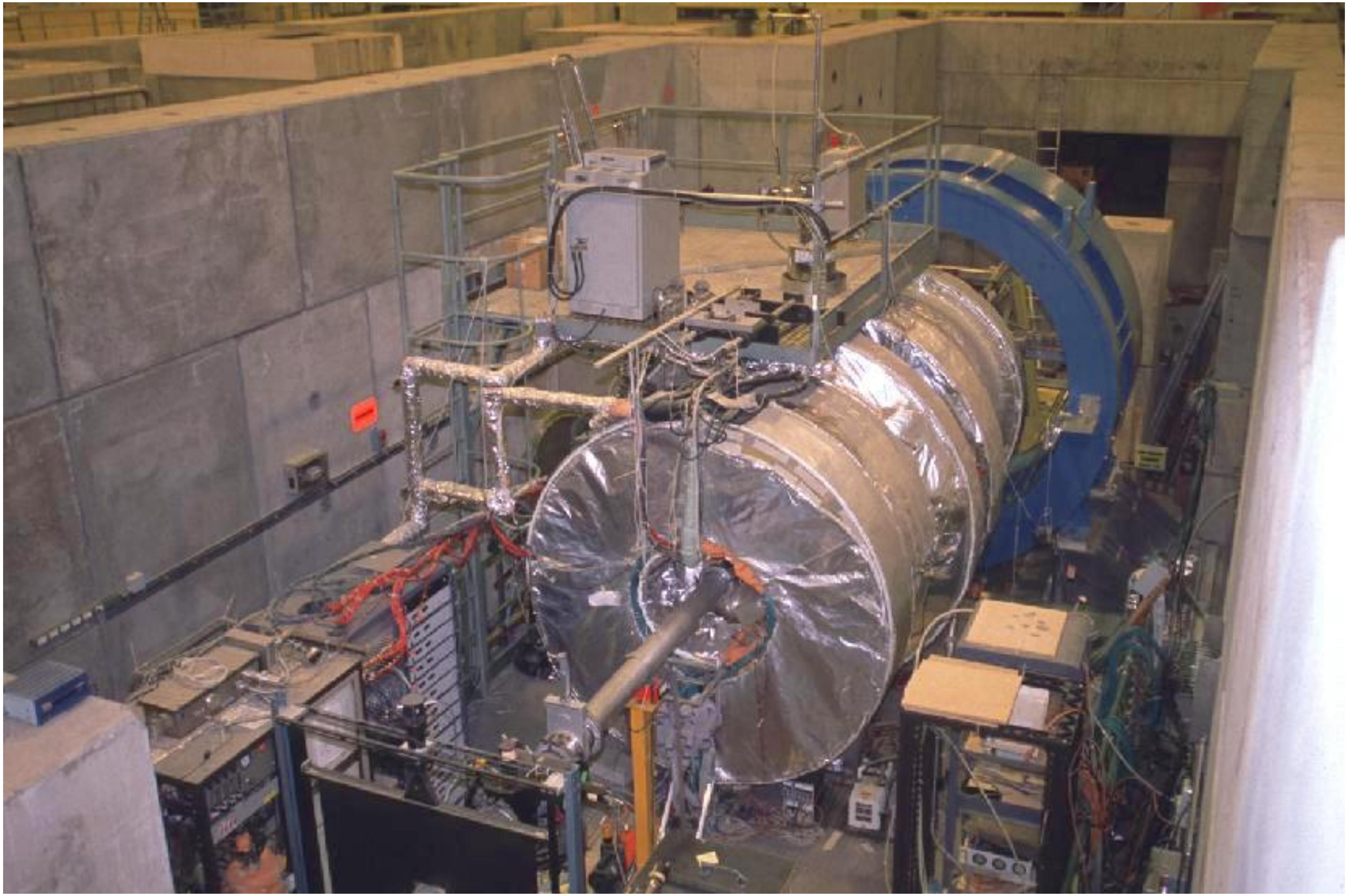
- SuperProtonSynchrotron (since 1976)
  - Parameters:
    - circumference: 6.9 km
    - beams for fixed target experiments
      - » protons up to 450 GeV/c
      - » lead ions up to 158 GeV/c
  - Past:
    - SppS proton-antiproton collider → discovery of vector bosons $W^{\pm}$, Z
  - Now:
    - injector for LHC
  - Experiments:
    - Switzerland: west area (WA)
    - France: north area (NA) → dileptons speak french!



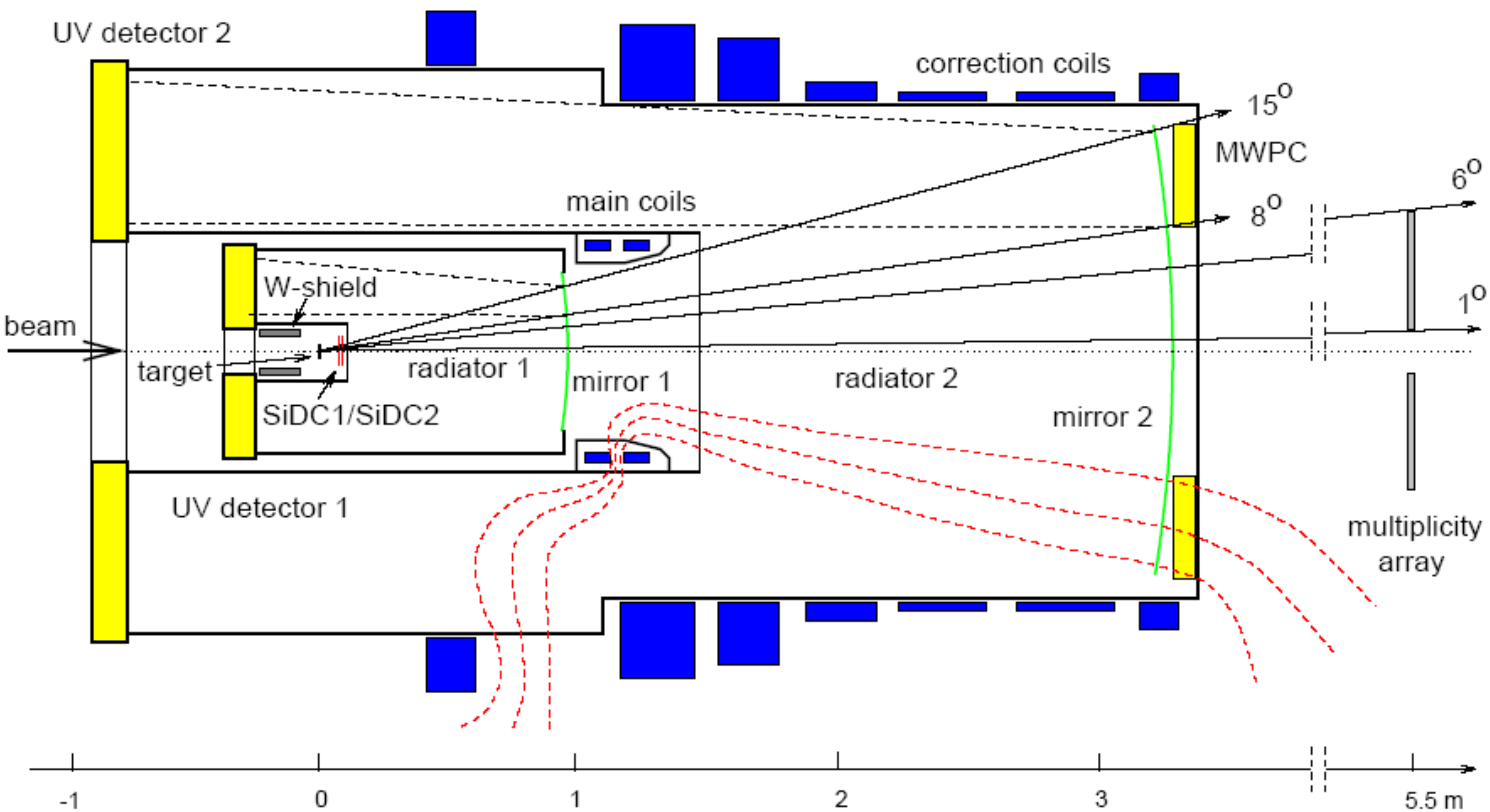
Dilepton Experiments at the SPS

Experiment	Channel	System	Mass range	Publications
HELIOS (NA34)	μμ/ee	p-Be (86)	low mass	Z. Phys. C68 (1995) 64
HELIOS-3 (NA34/3)	μμ	p-W, S-W (92)	low & intermediate	E. Phys. J. C13 (2000) 433
CERES (NA45)	ee	p-Be, p-Au, S-Au (92/93) Pb-Au (95) Pb-Au (96)	low mass	PRL (1995) 1272 Phys. Lett. B (1998) 405 Nucl. Phys. A661 (1999) 23
CERES-2 (NA45/2)	ee	Pb-Au 40 GeV (99) Pb-Au 158 GeV (2000)	low mass	PRL 91 (2002) 42301 preliminary data 2004
NA38/50	μμ	p-A, S-Cu, S-U, Pb-Pb	low (high m intermediate	E. Phys. J. C13 (2000) 69 E. Phys. J. C14 (2000) 443
NA60	μμ	p-A, In-In (2002,2003) p-A (2004)	low & intermediate	PRL 96 (2006) 162302

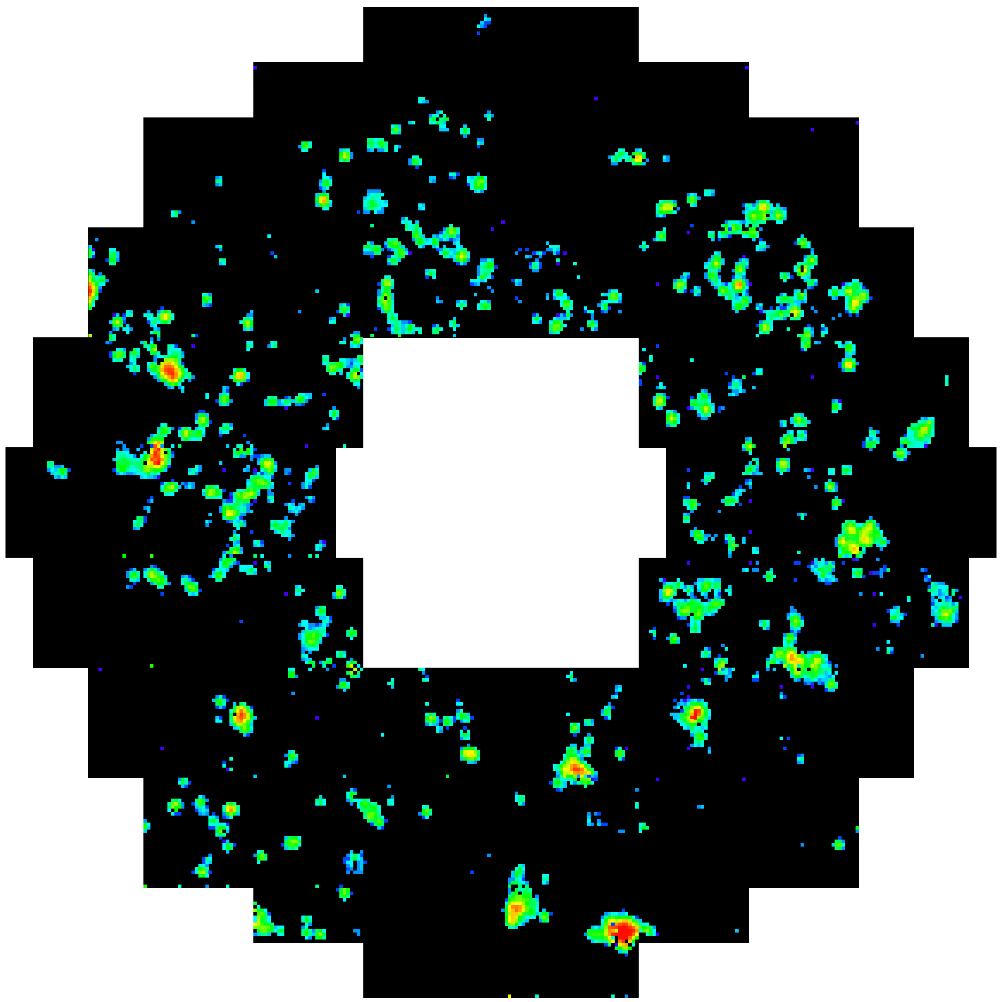
The CERES/NA45 Experiment

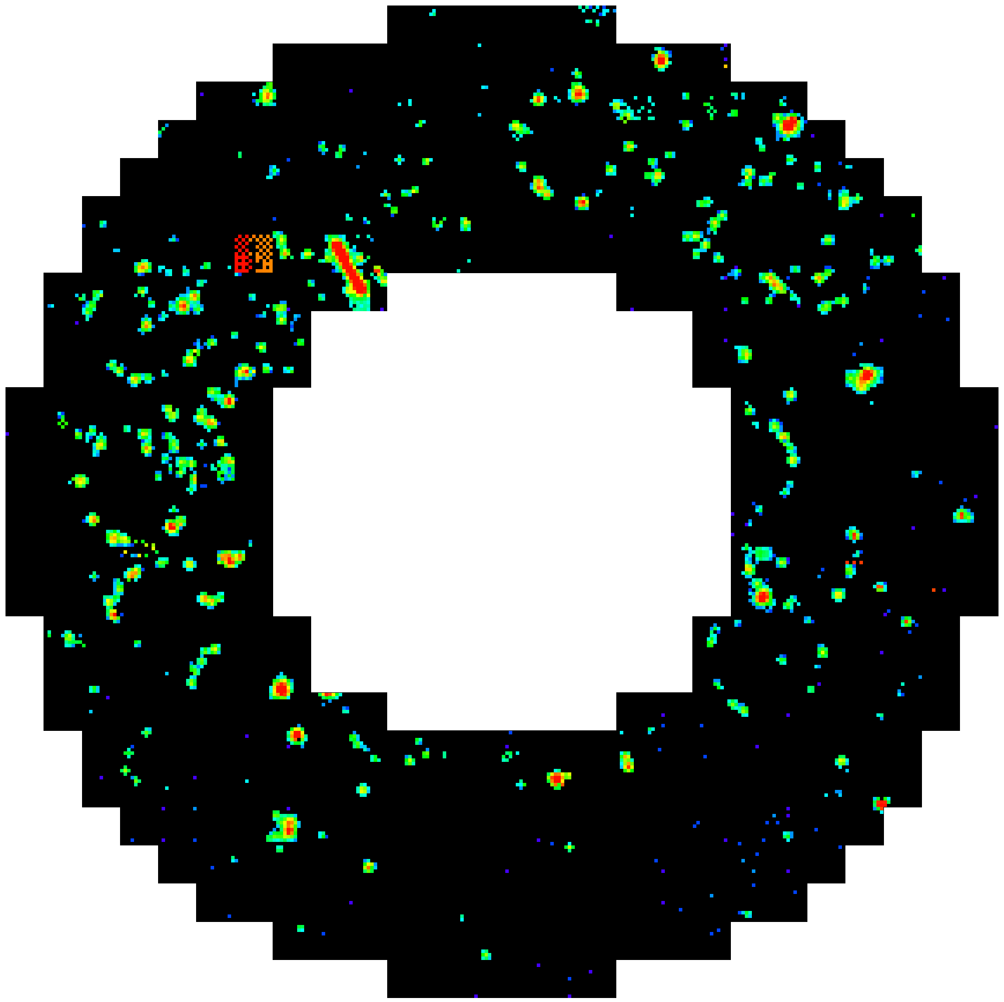


Experimental Setup: CERES-1



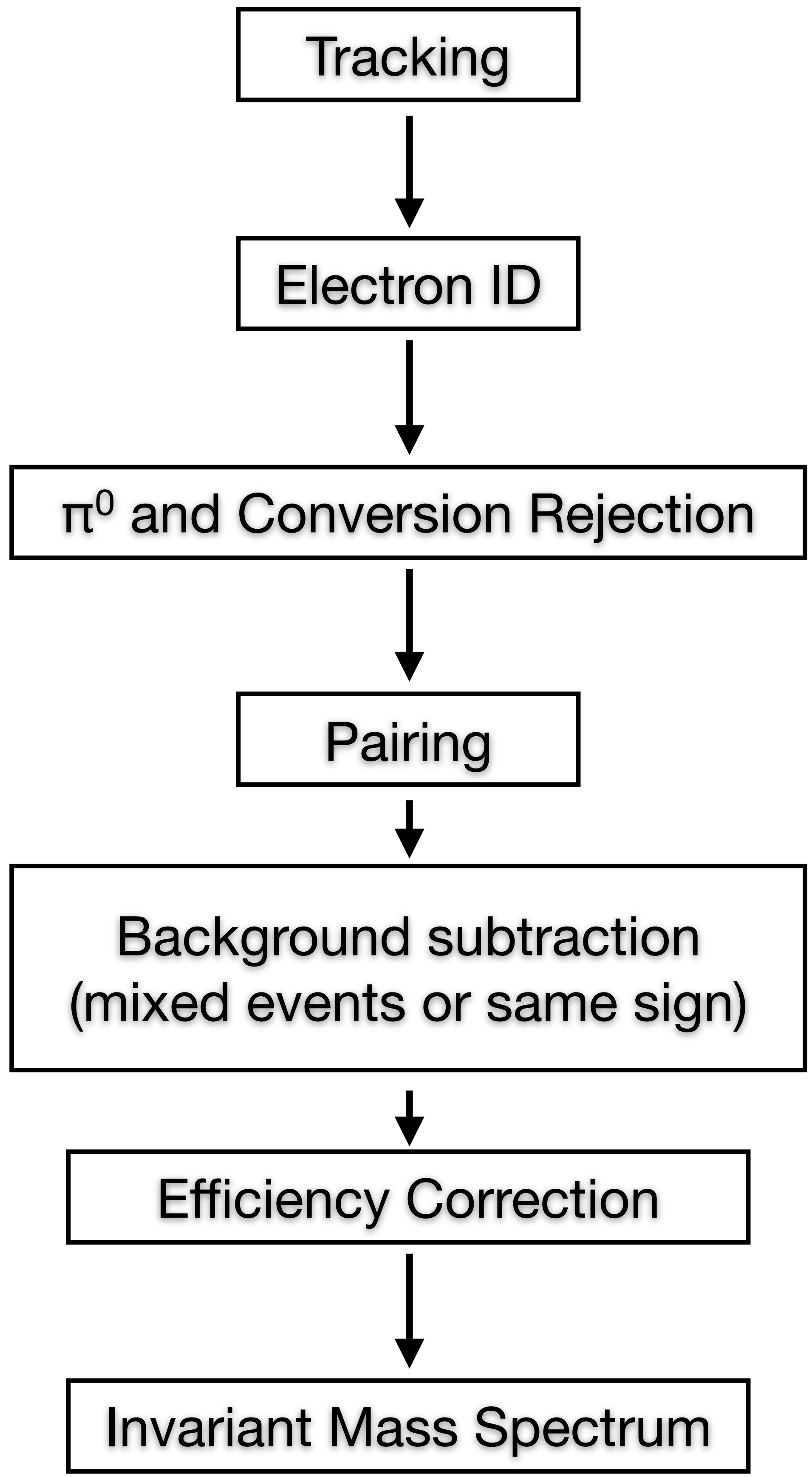
Electron Identification: RICH





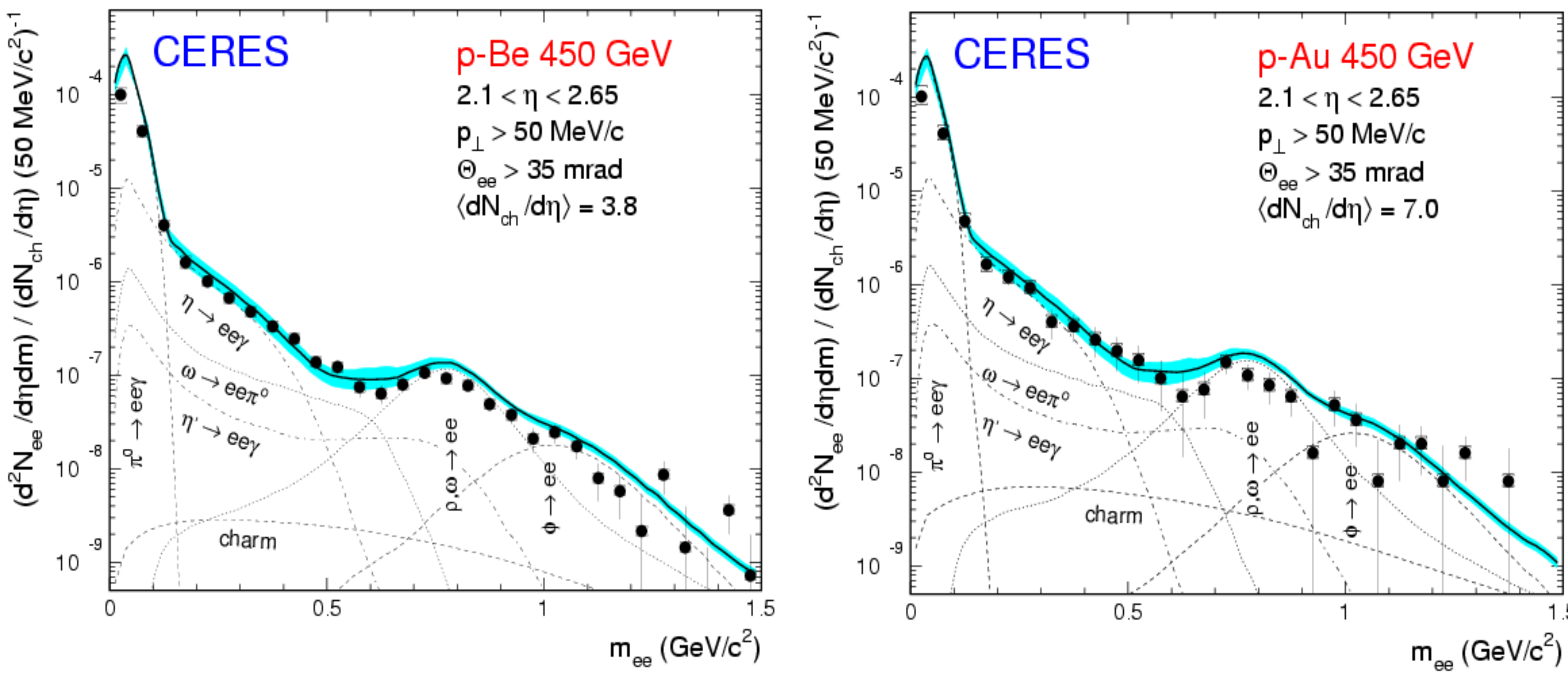
- Main tool for electron ID
- Use the number of hits per ring (and their analog sum) to recognise single and double rings

Dielectron Analysis Strategy



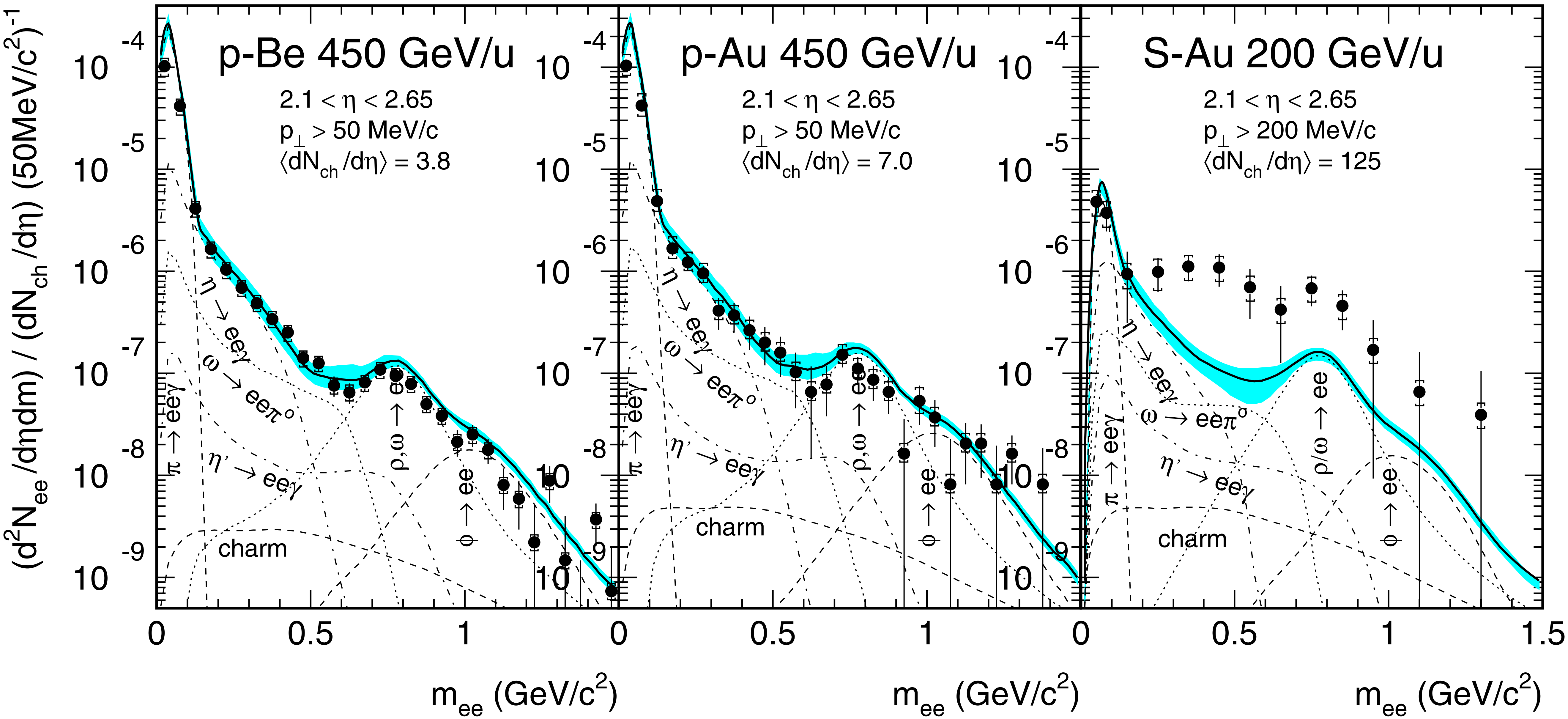
e^+e^- in p-Be & p-Au collisions

- Dielectron mass spectra and expectation from a ‘cocktail’ of known sources
  - Dalitz decays of neutral mesons ($\pi^0 \rightarrow \gamma\, e^+e^-$ and η, ω, η’, ϕ)
  - Dielectron decays of vector mesons (ρ, ω, ϕ → e^+e^-)
  - Semileptonic decays of particles carrying charm quarks



➡ Dielectron production in p-p and p-A collisions at SPS well understood in terms of known hadronic sources

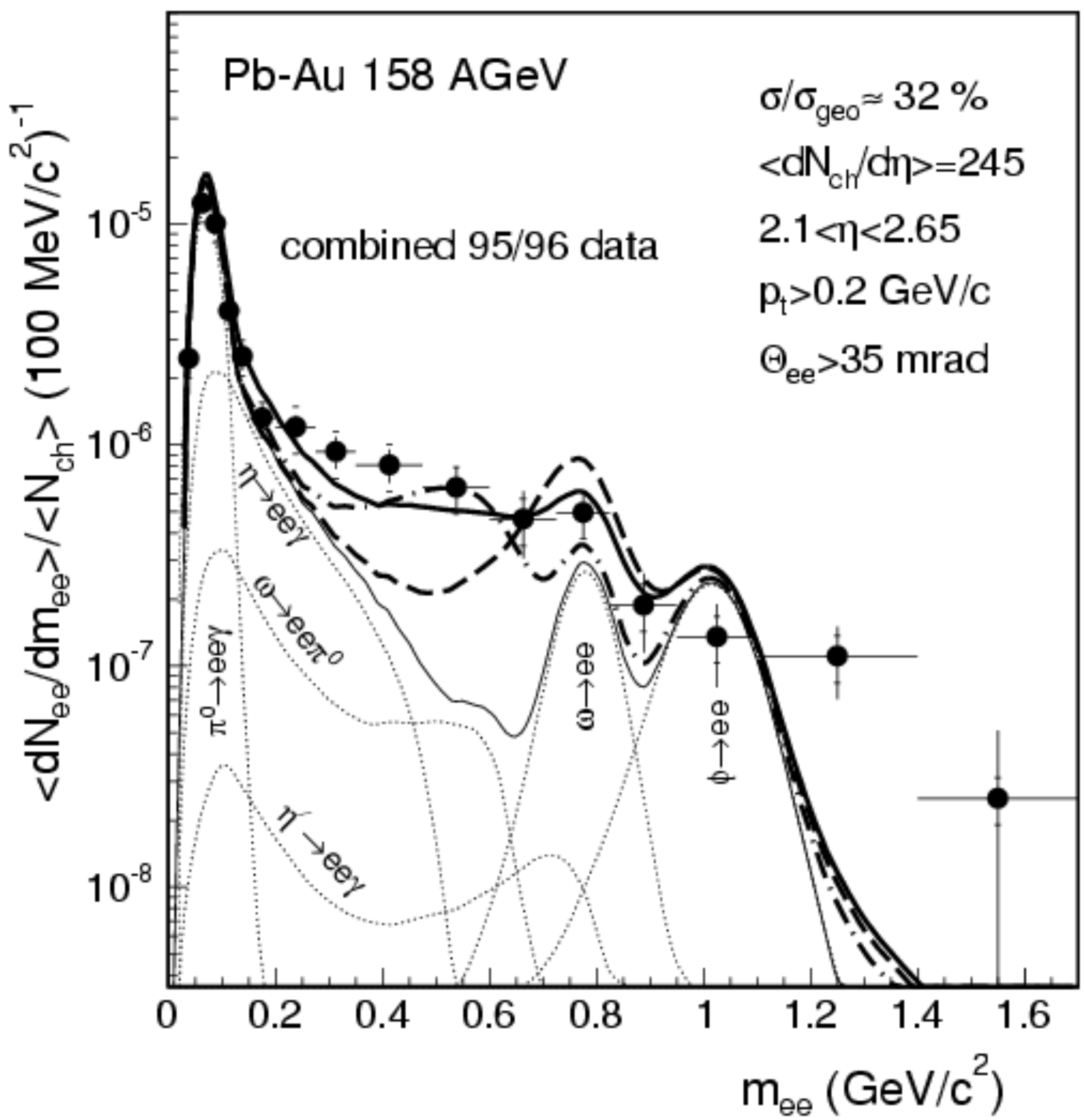
What About Heavy-Ion Collisions?



- Discovery of low mass e^+e^- enhancement in 1995
  - Significant excess in S-Au (factor ~5 for m>200 MeV)

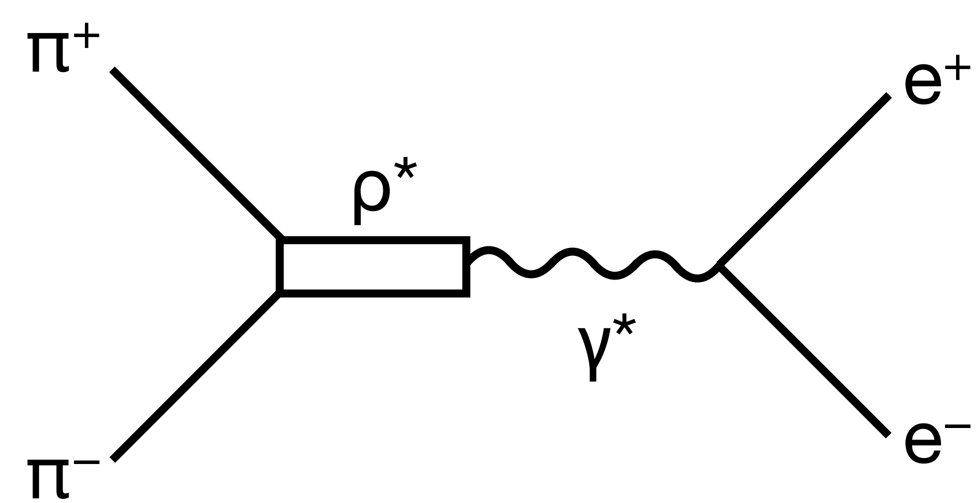
As Heavy As It Gets: Pb-Au

CERES EPJ C41(2005)475



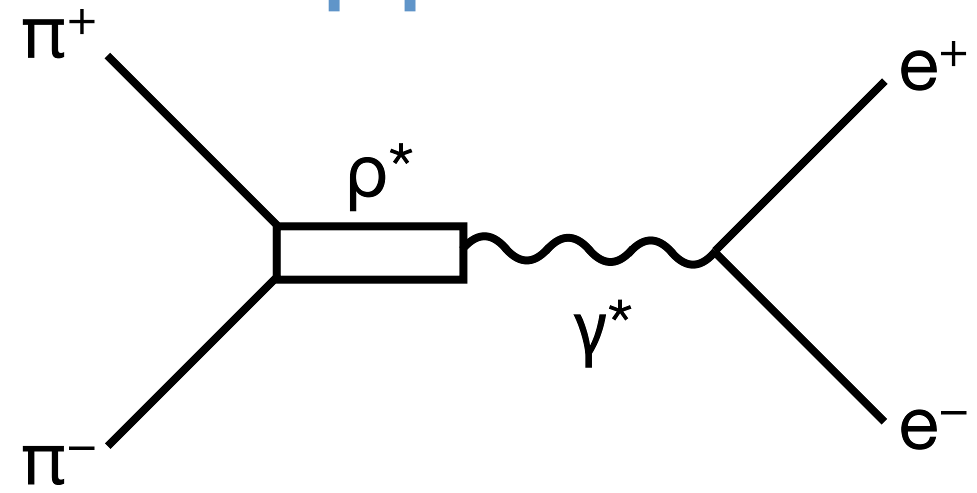
- Dielectron excess at low and intermediate masses in HI collisions is well established
  - Onset at ~2 m_π → π-π annihilation?
  - Maximum below ρ meson near 400 MeV/c^2

➡ Hint for modified ρ meson in dense matter

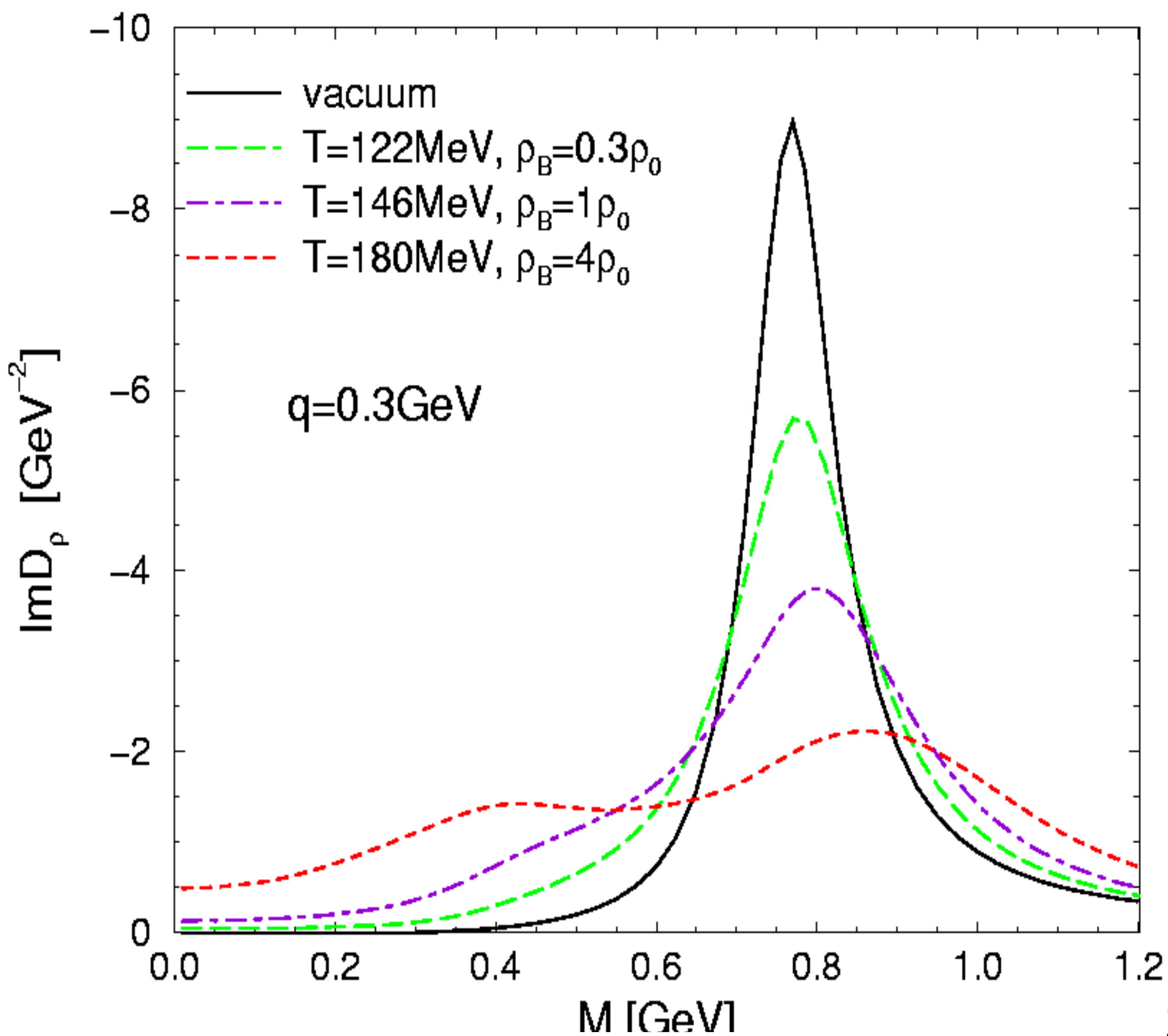


π-π annihilation: theoretical approaches

- Low mass enhancement due to π-π annihilation?
  - Spectral shape dominated by ρ meson
- Vacuum ρ
  - Vacuum values of width and mass
- In-medium ρ
  - Brown-Rho scaling
    - Dropping masses as chiral symmetry is restored
  - Rapp-Wambach melting resonances
    - Collision broadening of spectral function
    - Only indirectly related to CSR
  - Medium modifications driven by baryon density
- Model space-time evolution of collision

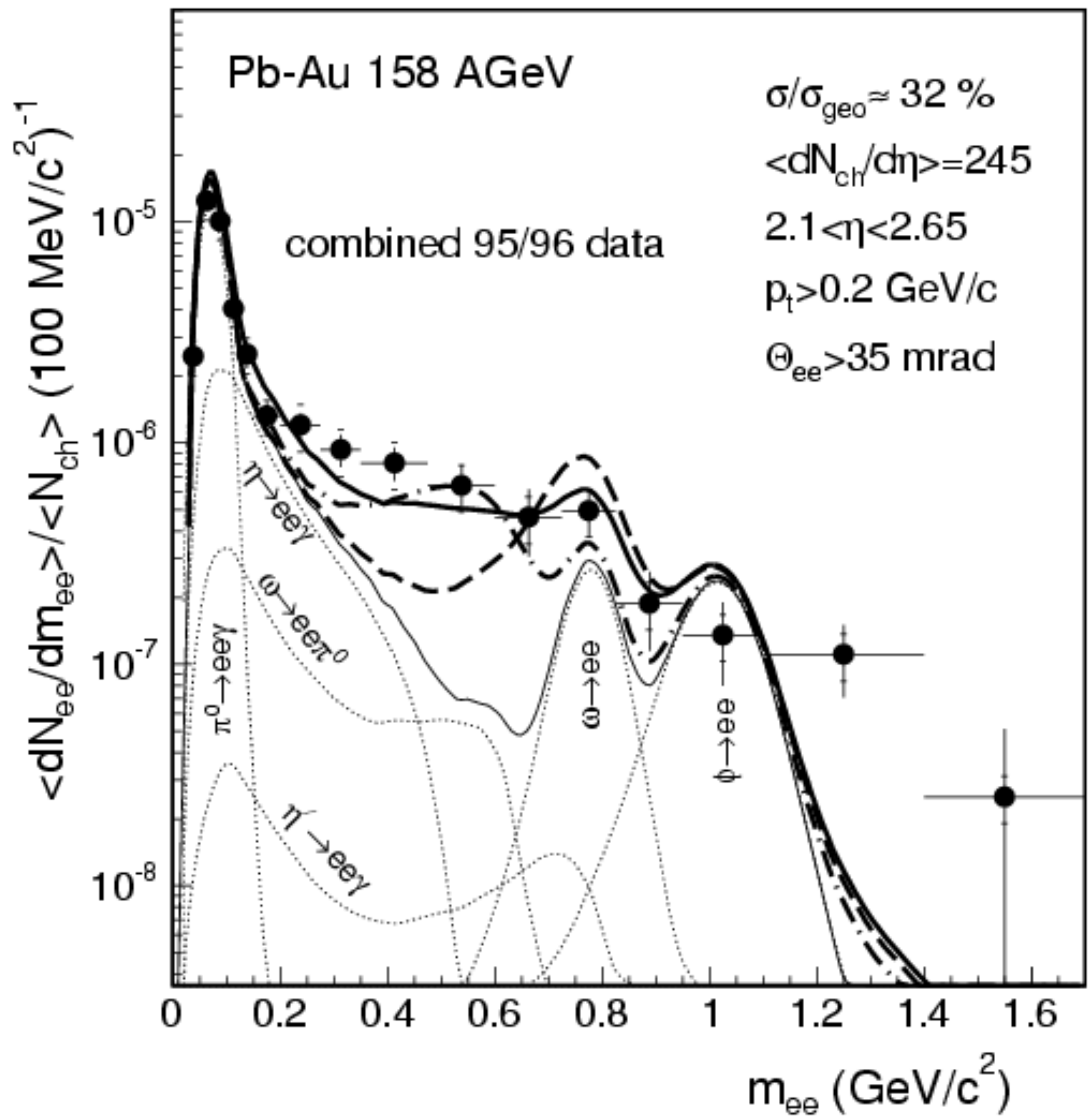


$$\frac{m_\rho^*}{m_\rho} = \left(\frac{\langle\overline{\psi}\psi\rangle_{\rho^*}}{\langle\overline{\psi}\psi\rangle_{\rho_0}}\right)^{1/3} = 1 - 0.16\frac{\rho^*}{\rho_0}$$



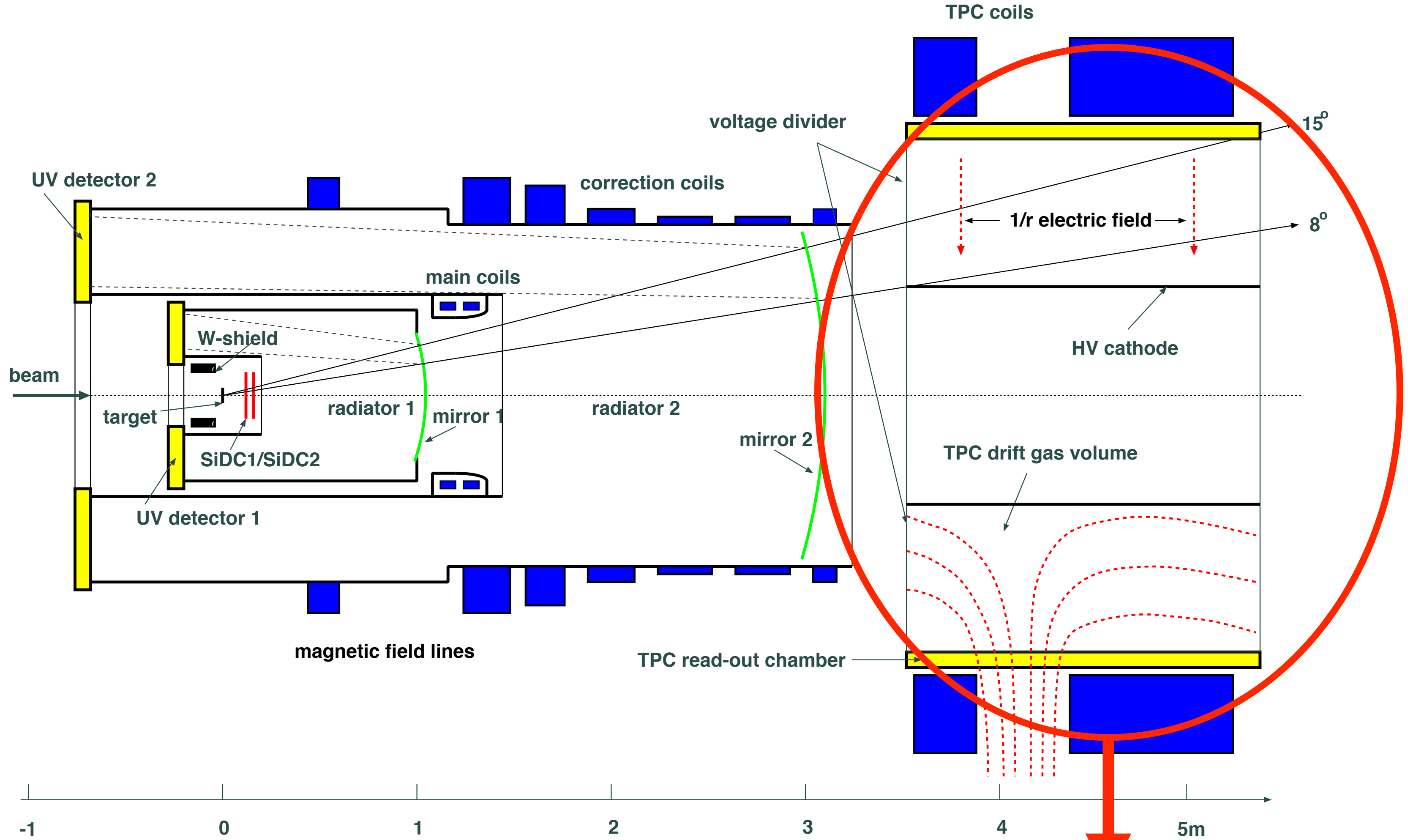
Results from the SPS: CERES

- Attempt to attribute the observed excess to
  - vacuum ρ meson (- - - - - -)
    - inconsistent with data
    - overshoot in ρ region
    - undershoots @ low mass
  - modification ρ meson
    - needed to describe data
    - data do not distinguish between:
      - (solid line) » broadening or melting of ρ-meson (Rapp-Wambach)
      - (dash-dot line) » dropping masses (Brown-Rho)
- Indication for medium modifications, but data are not accurate enough to distinguish models



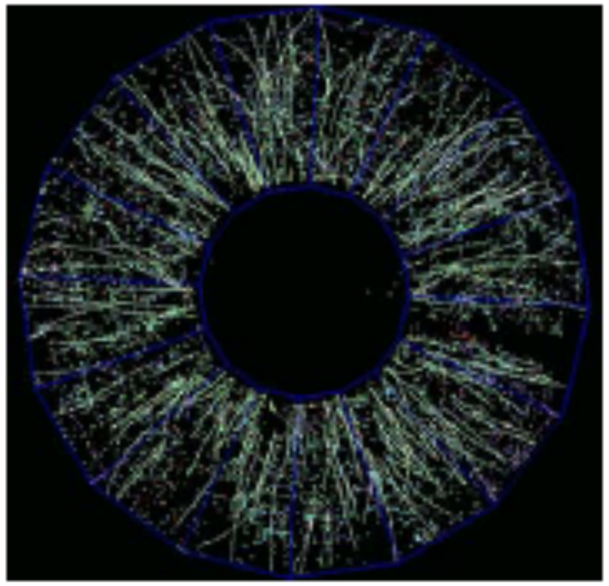
- Largest discrimination between ρ/ω and ϕ
  → need mass resolution!

CERES-1 → CERES-2



- Addition of a TPC to CERES
  - Improved momentum resolution
  - Improved mass resolution
  - dE/dx → hadron identification and improved electron ID
  - Inhomogeneous magnetic field → a nightmare to calibrate

radial drift TPC: momentum and energy loss



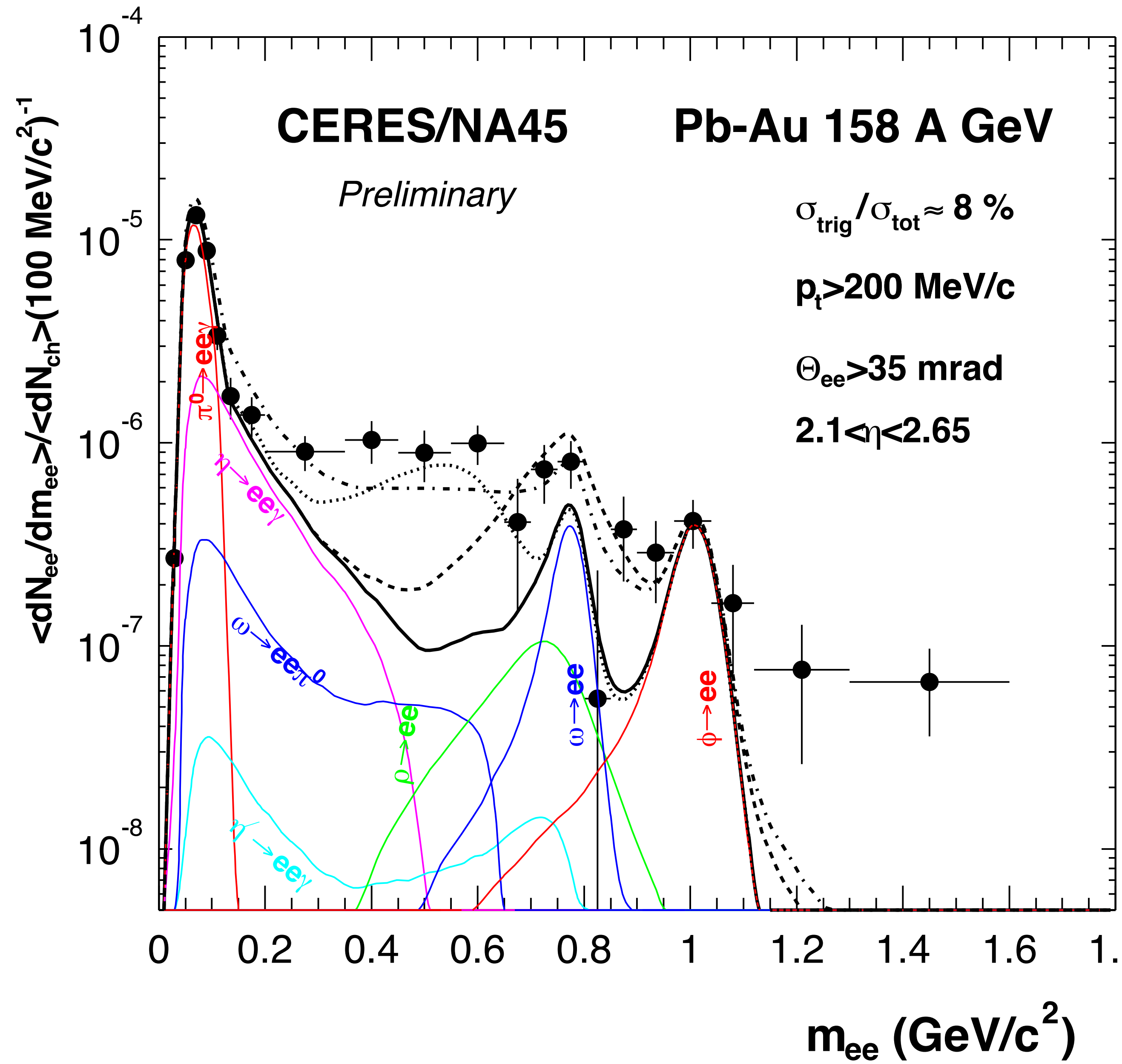
$\Delta p/p = 2\% \oplus 1\% * p/\mathrm{GeV}$

$\Delta m/m = 3.8\ \%$ for ϕ

$\Delta(dE/dx)/(dE/dx) = 10\%$

CERES-2 Result

- CERES-1 results persists
  - strong enhancement in the low-mass region
  - enhancement factor (0.2 < m < 1.1 GeV/c2): 3.1 ± 0.3 (stat.)
- But the improvement in mass resolution is not outrageous
- Vacuum ρ not enough to reproduce the data
- in-medium modifications of ρ:
  - broadening ρ spectral shape (Rapp and Wambach)
  - dropping ρ meson mass (Brown et al.)



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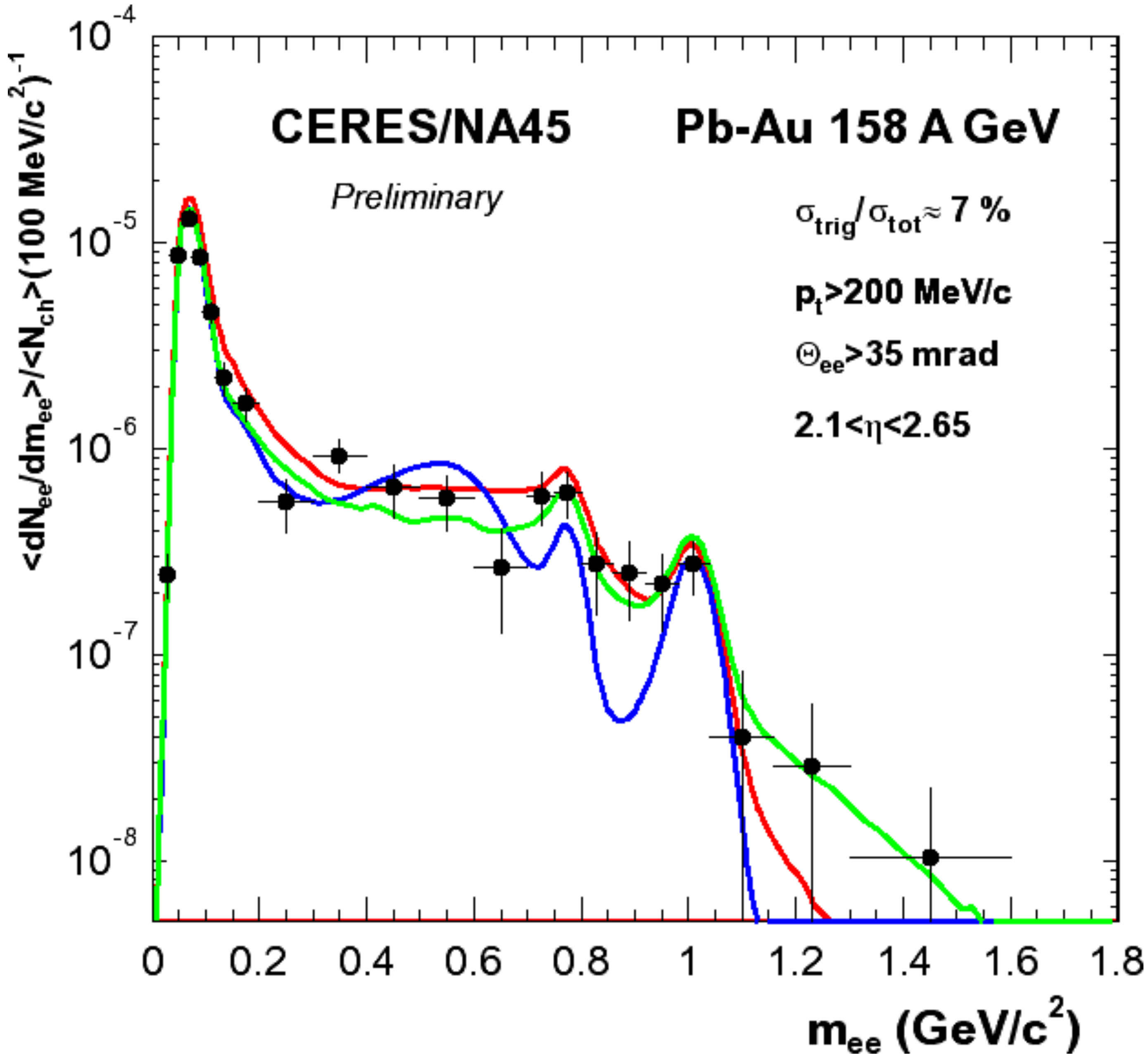

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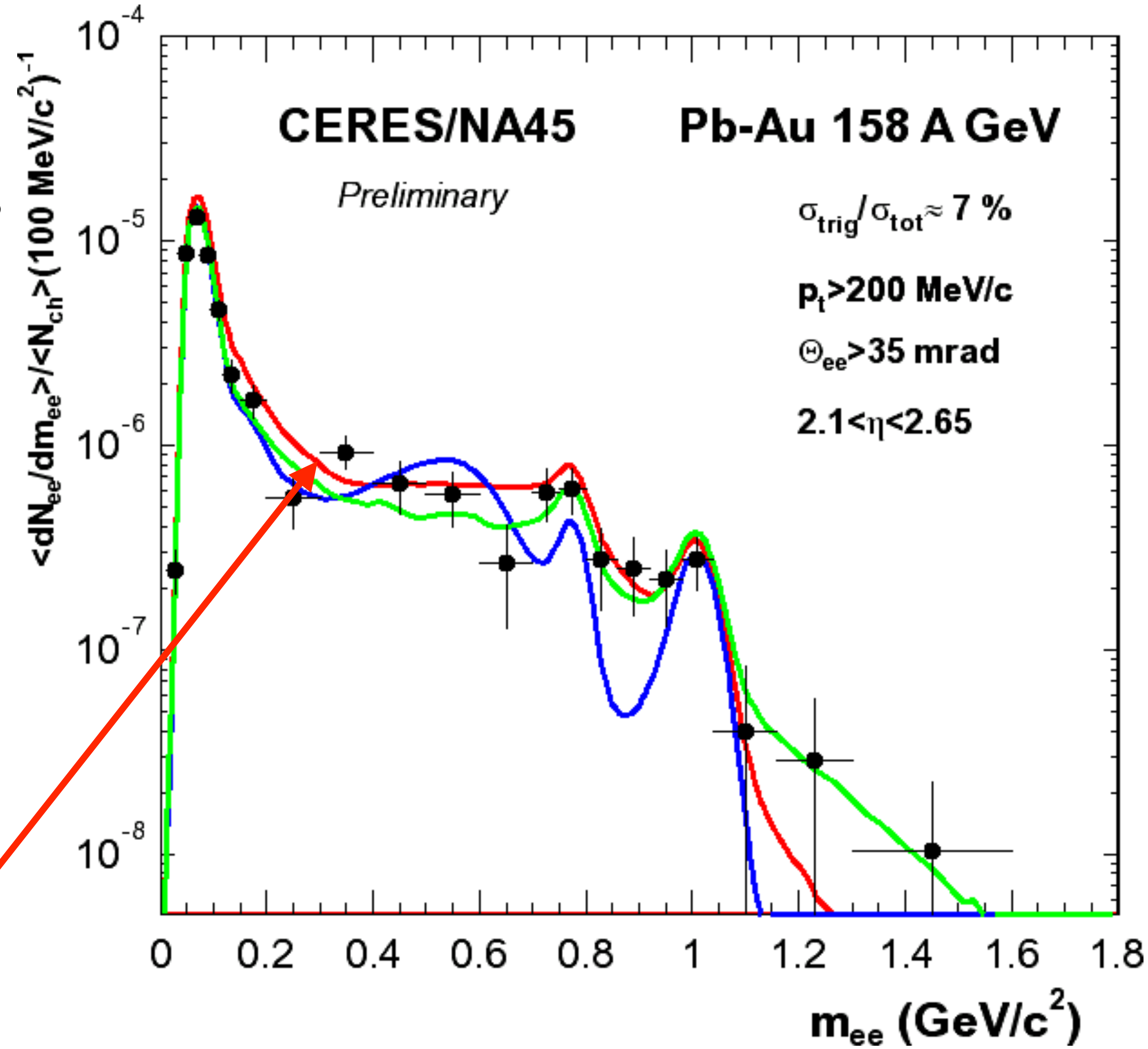

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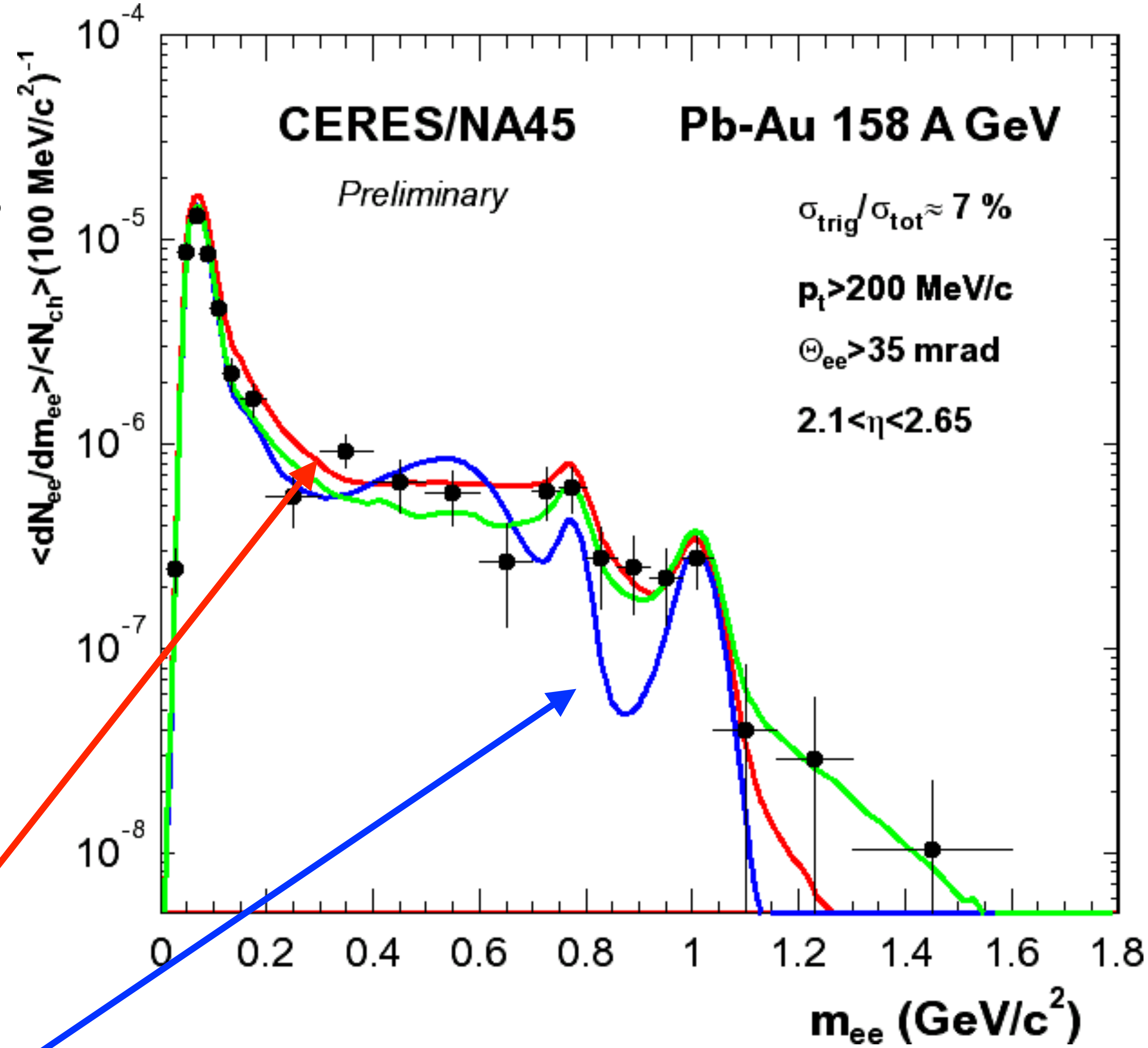

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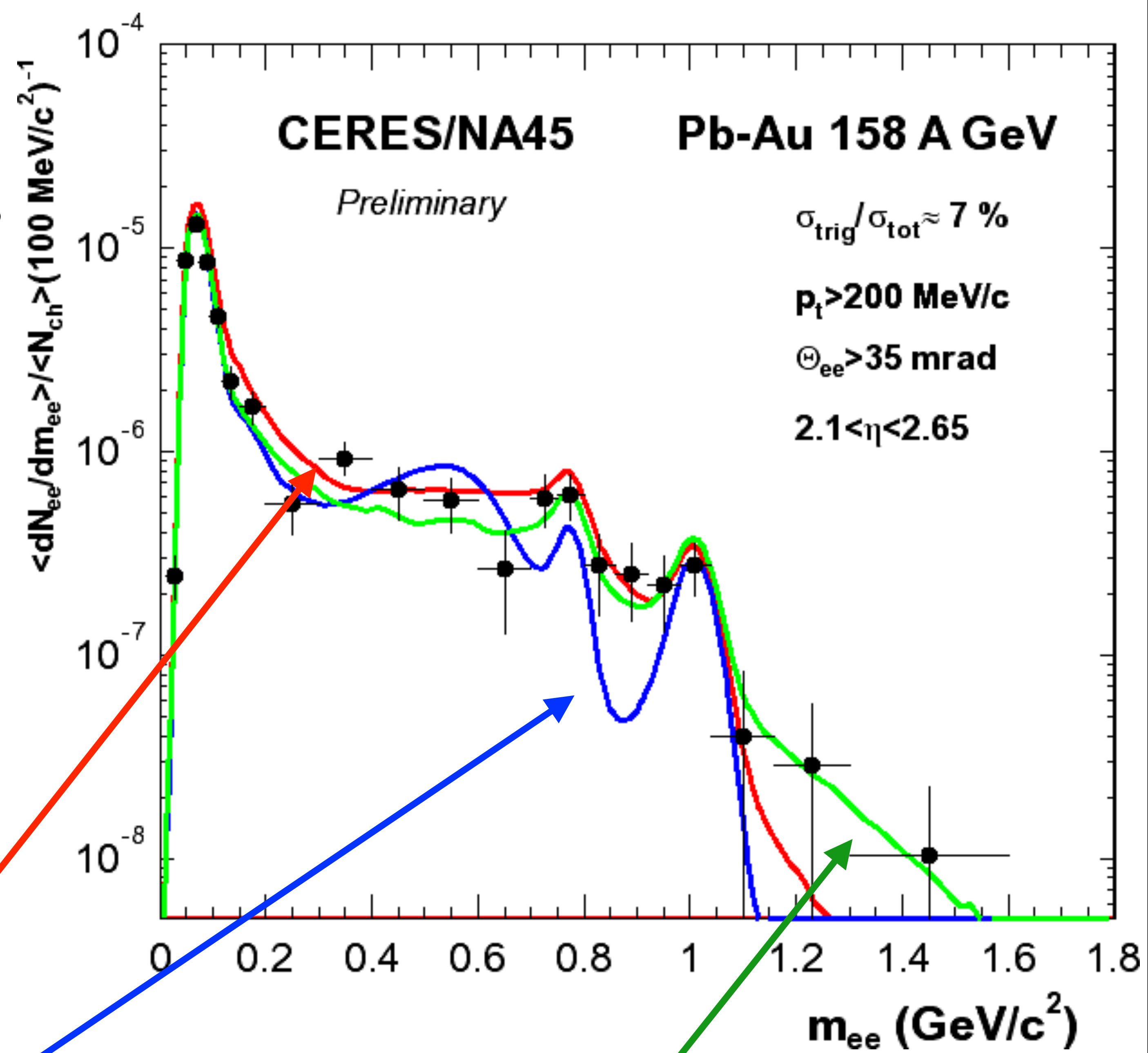
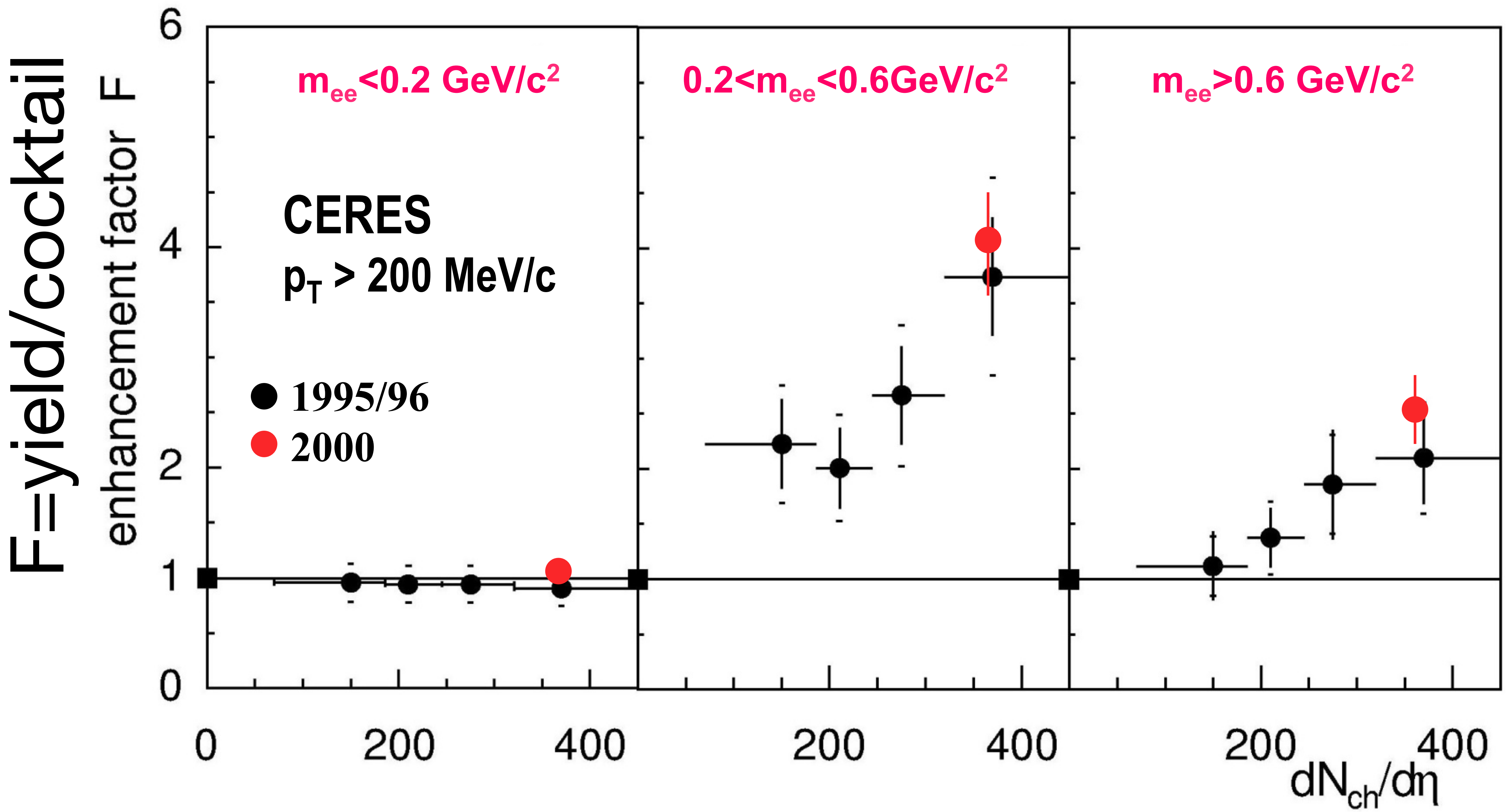


- thermal radiation e^+e^- yield calculated from qq annihilation in pQCD (B.Kämpfer et al.)

Centrality Dependence of Excess



- Naïve expectation: quadratic multiplicity dependence
  - Medium radiation proportional to particle density squared
- More realistic: smaller than quadratic increase
  - Density profile in transverse plane
  - Life time of reaction volume

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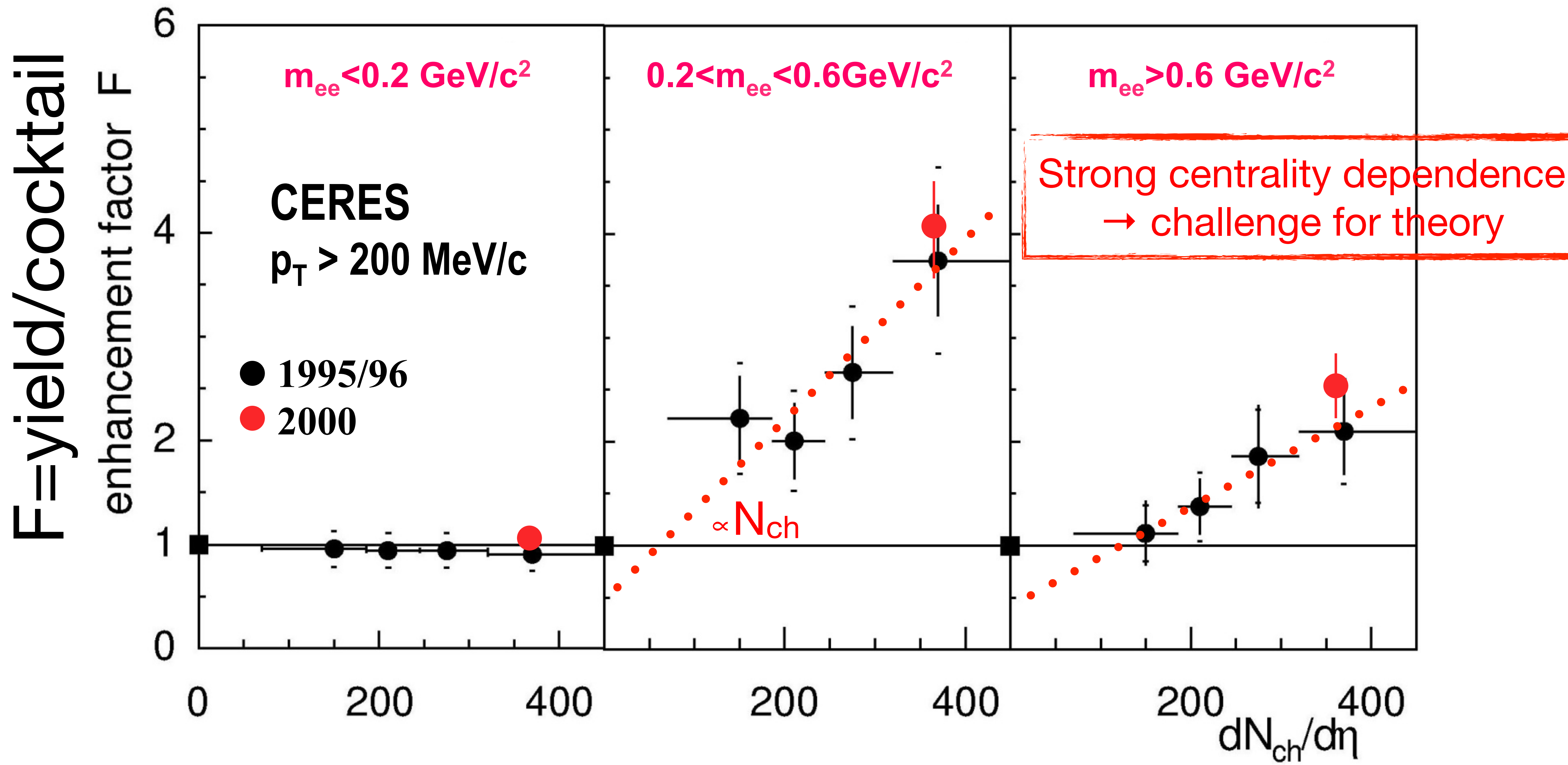

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What Did We Learn From CERES?

- First systematic study of e^+e^- production in elementary and HI collisions at SPS energies
  - p-p and p-A collisions are consistent with the expectation from known hadronic sources
  - A strong low-mass low-p_T enhancement is observed in HI collisions

➡ Consistent with in-medium modification of the ρ meson

➡ Data cannot distinguish between two scenarios
  - Dropping ρ mass as direct consequence of CSR
  - Collisional broadening of ρ in dense medium

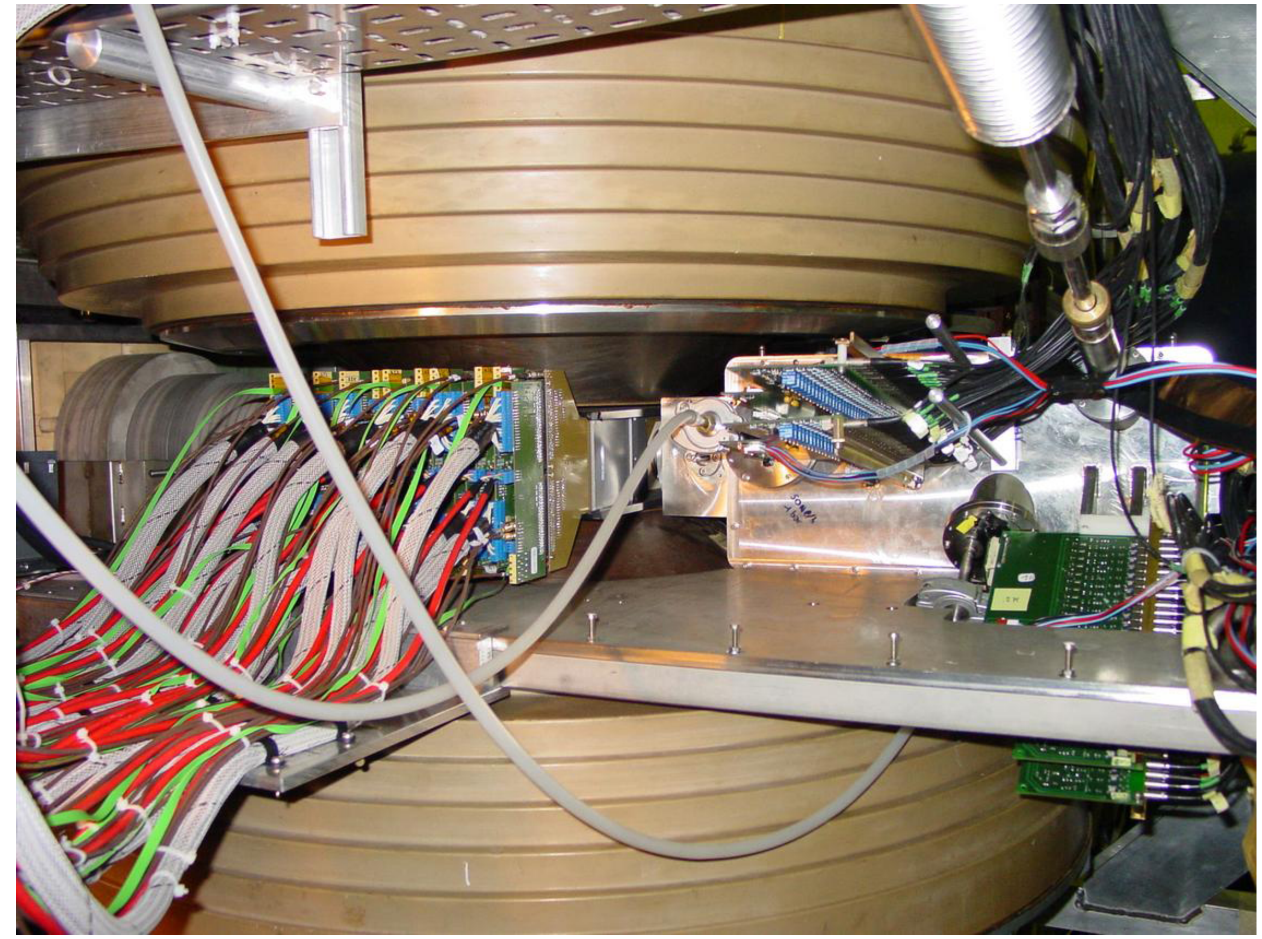
- WHAT IS NEEDED FOR PROGRESS?
  - STATISTICS
  - MASS RESOLUTION

How to Overcome these limitations

- More statistics
  - Run forever → not an option
  - Higher interaction rate
    - Higher beam intensity
    - Thicker target
  - Needed to tolerate this
    - Extremely selective hardware trigger
    - Reduced sensitivity to secondary interactions, e.g. in target
  - ➡ Cannot be done with dielectrons as a probe, but dimuons are just fine!

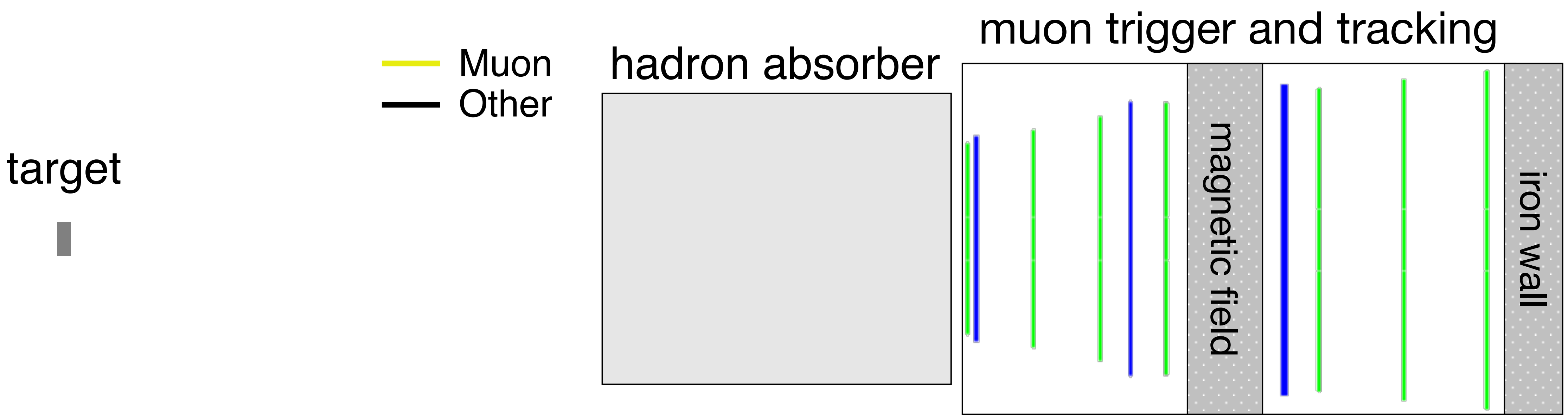
- Better mass resolution
  - Stronger magnetic field
  - Detectors with better position resolution
  - ➡ Silicon tracker embedded in strong magnetic field!

The NA60 Experiment



- A huge absorber and muon spectrometer (and trigger)
- And a tiny, high resolution, radiation hard vertex spectrometer

Standard $\mu^+\mu^-$ detection: NA50



- Thick hadron absorber to reject hadronic background
- Trigger system based on fast detectors to select muon candidates (1 in 10^4 PbPb collisions at SPS energy)
- Muon tracks reconstructed by a spectrometer (tracking detectors + magnetic field)
- Extrapolate muon tracks back to the target taking into account multiple scattering and energy loss, but …
  - Poor reconstruction of interaction vertex (σ_z ~10 cm)
  - Poor mass resolution (80 MeV at the ϕ)

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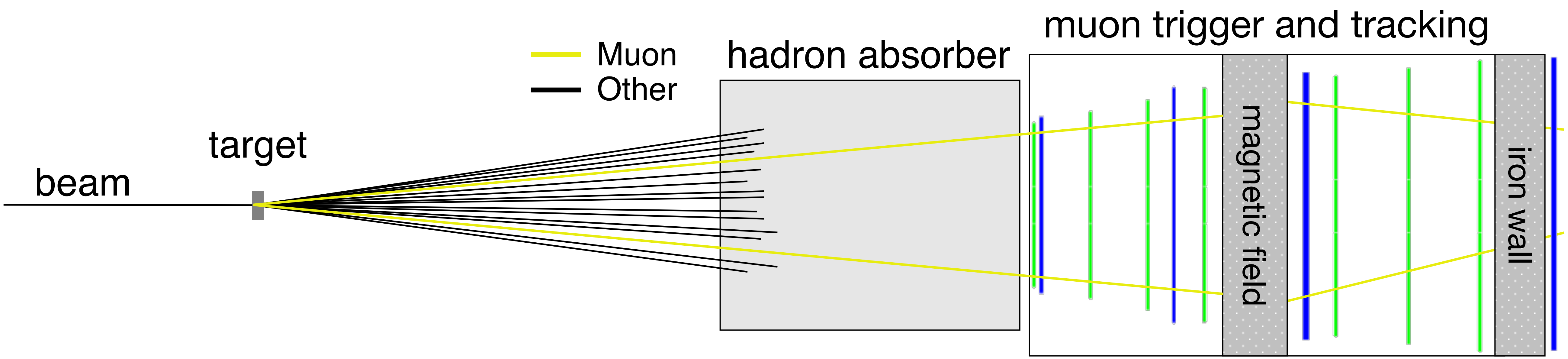

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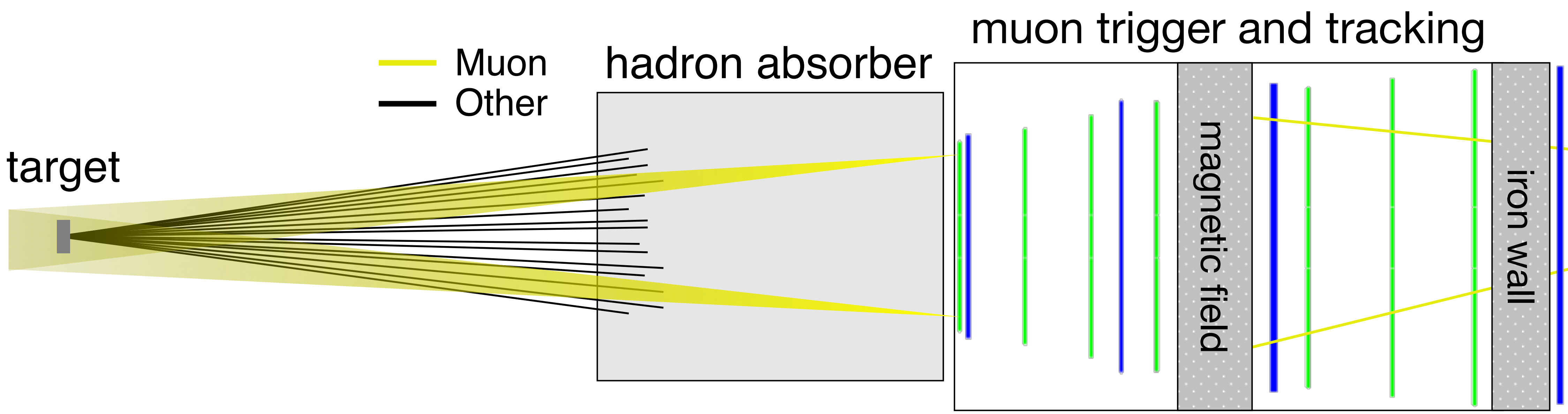

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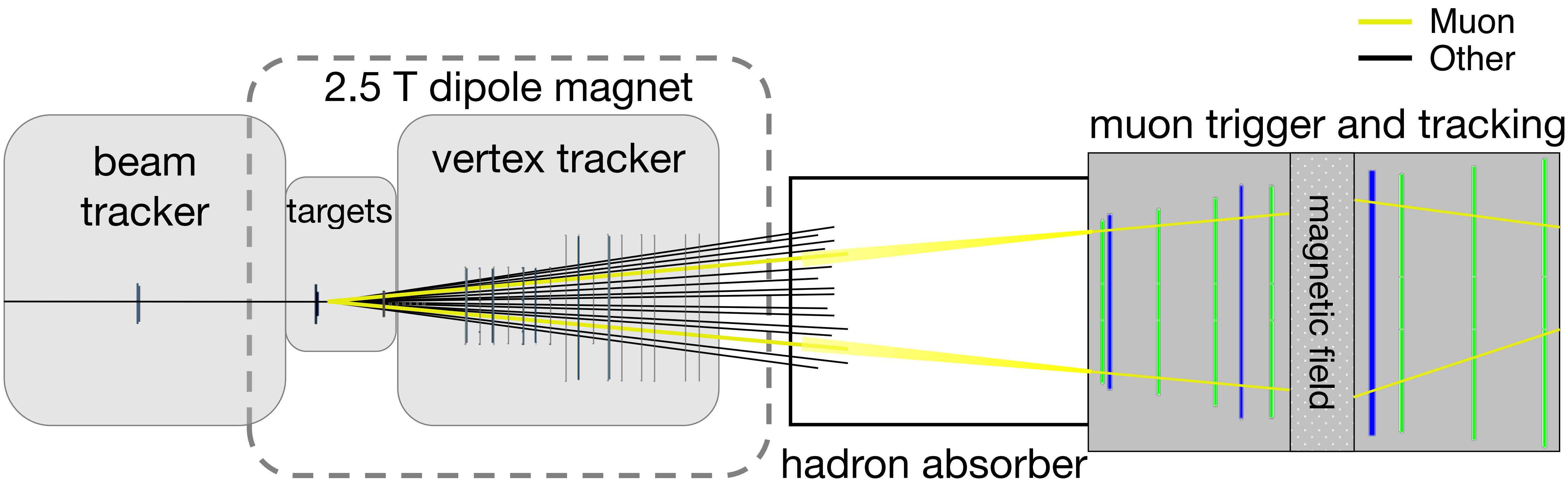
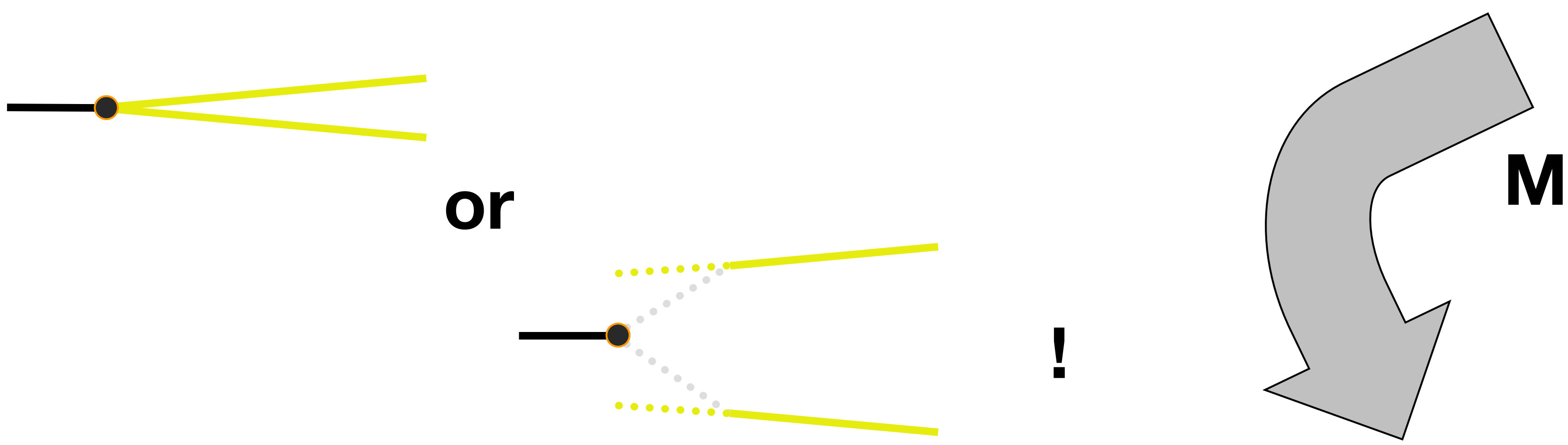
A step forward: the NA60 case

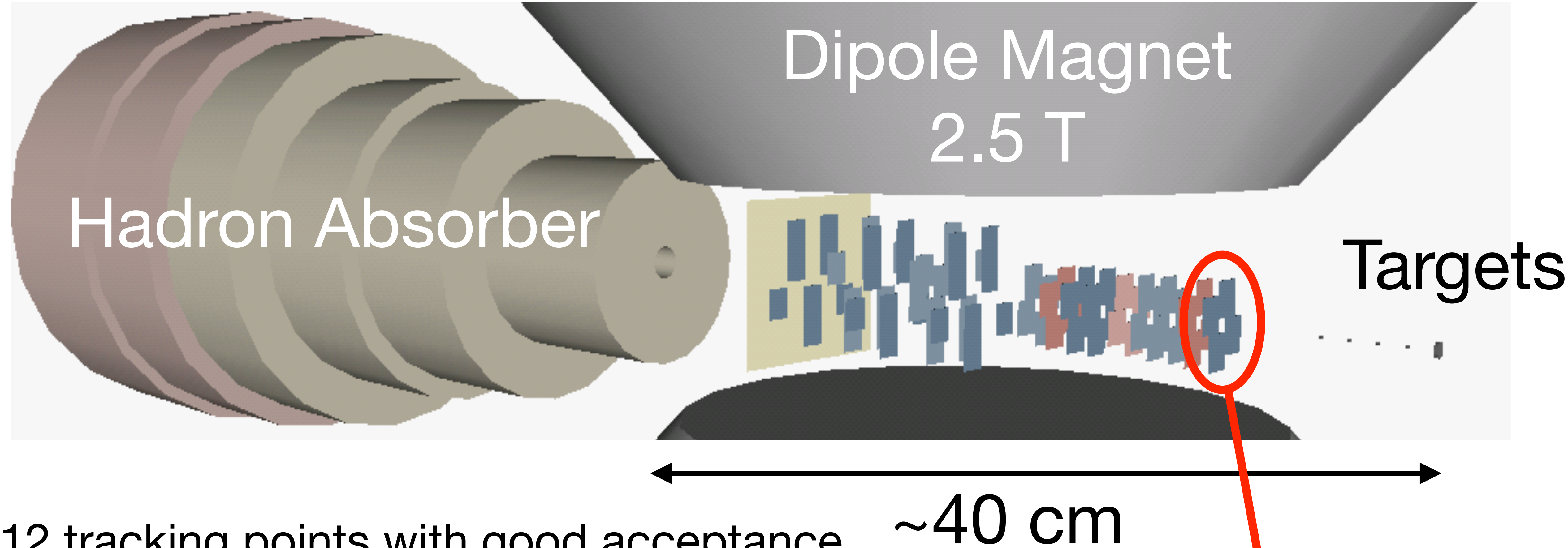




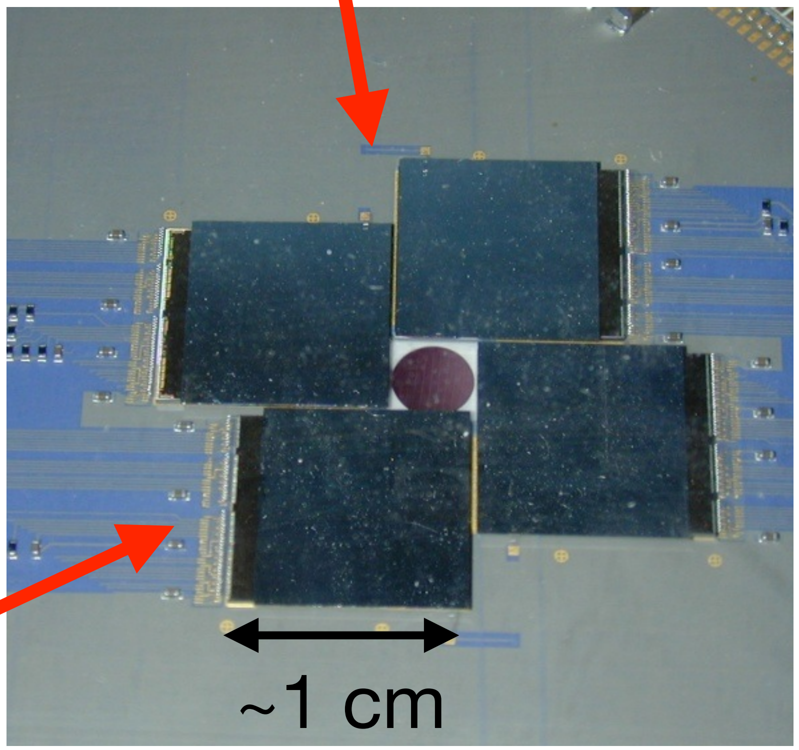
Matching of muon tracks

- Origin of muons can be determined accurately
- Improved dimuon mass resolution

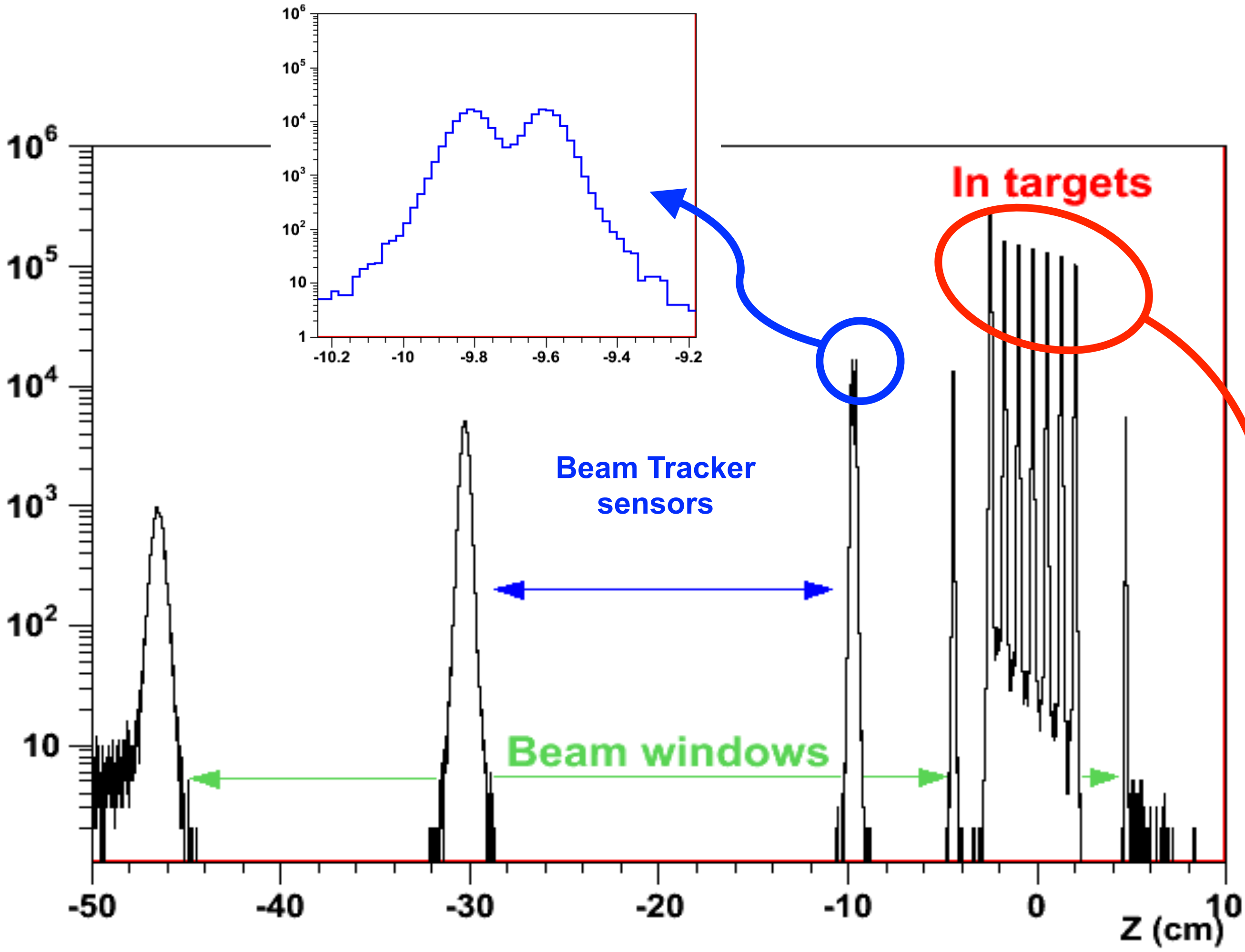
The NA60 Pixel Vertex Spectrometer

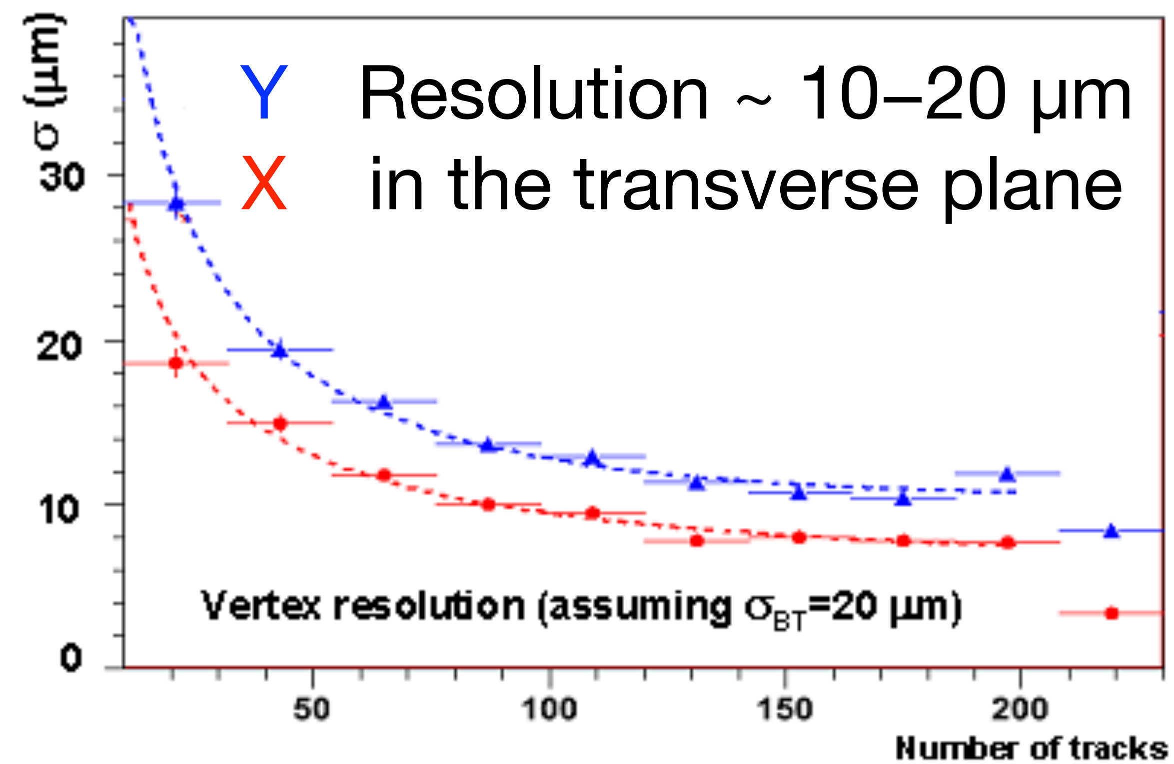


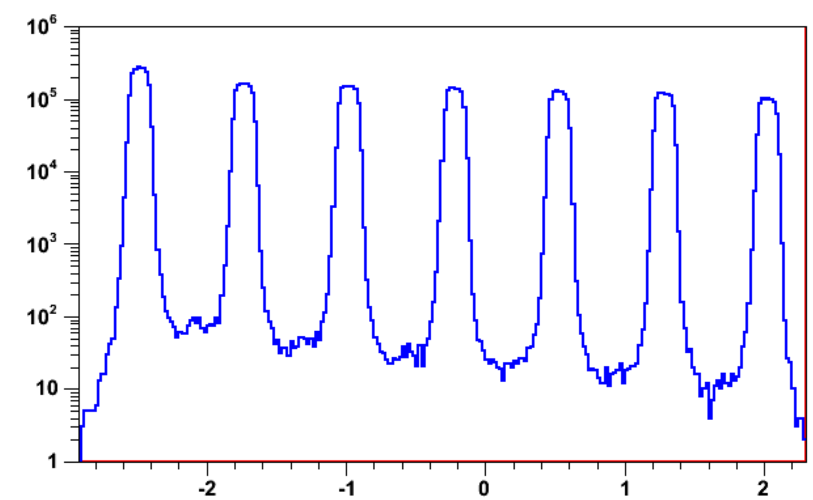
- 12 tracking points with good acceptance
  - 8 small 4-chip planes
  - 8 large 8-chip planes in 4 tracking stations
- ~3% X0 per plane
  - 750 µm Si readout chip
  - 300 µm Si sensor
  - ceramic hybrid
- 800 000 readout channels in 96 pixel assemblies



Vertexing in NA60







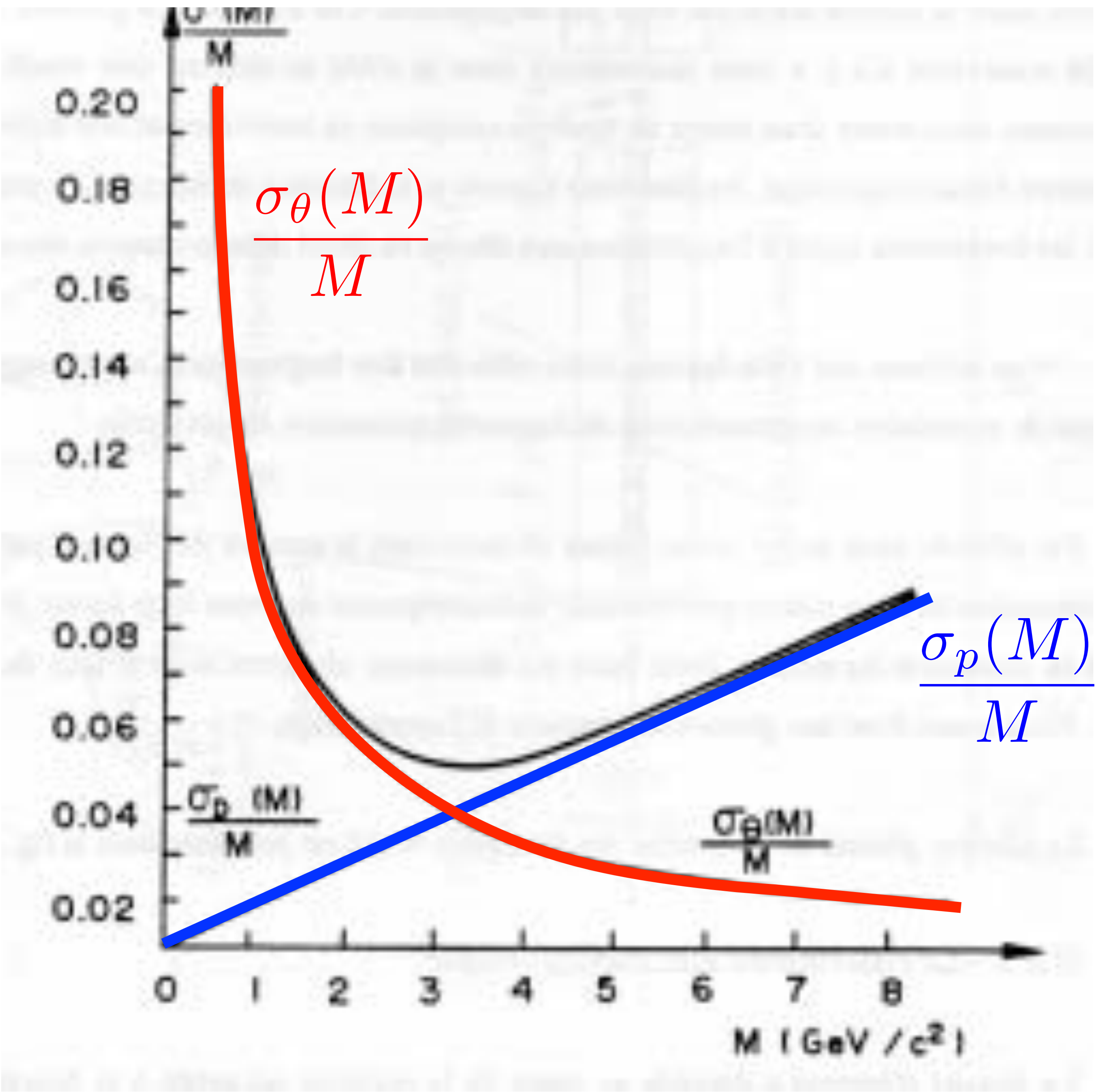
- σ_Z ~ 200 μm along the beam direction
- Good vertex identification with ≥ 4 tracks

Extremely clean target identification (Log scale!)

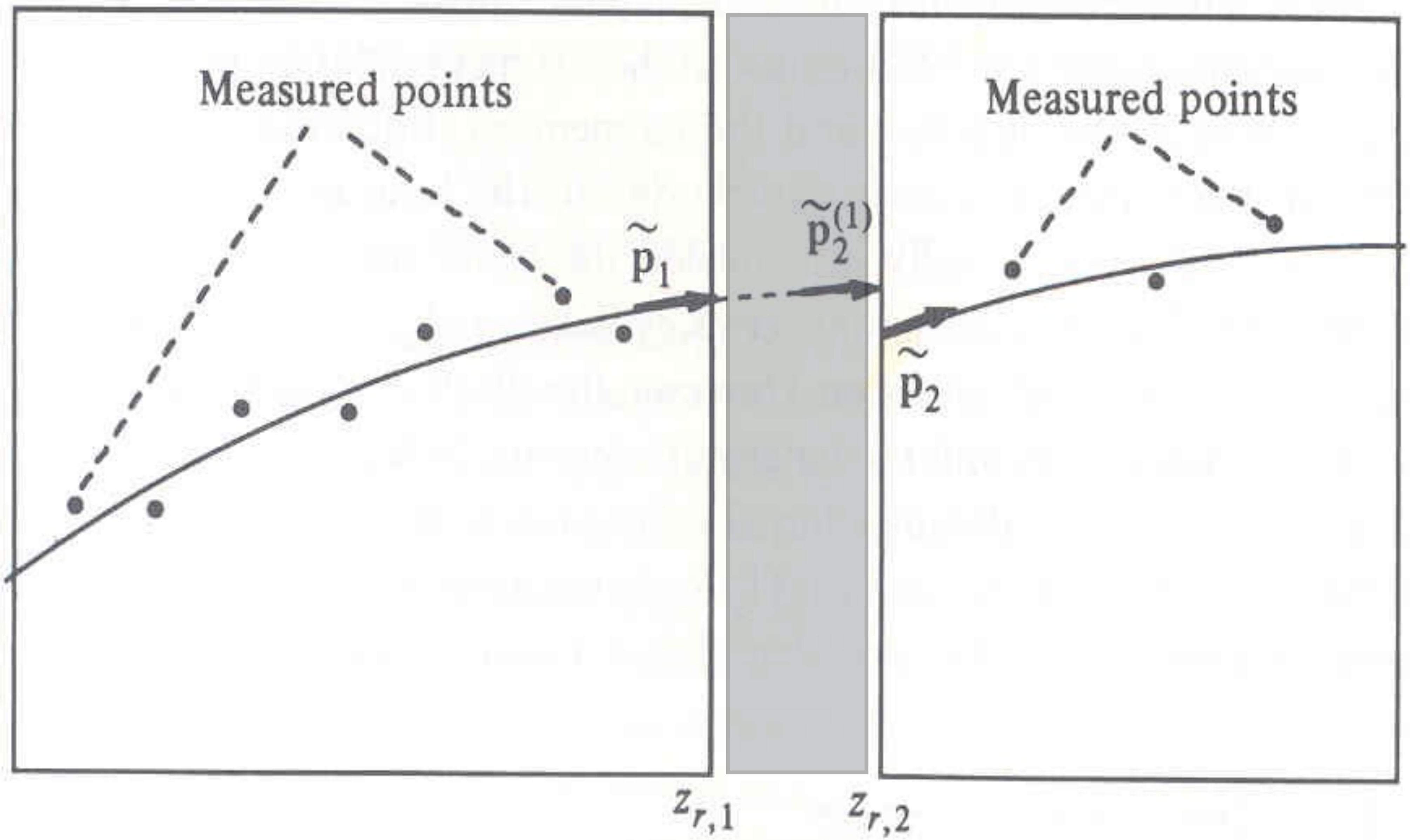
Contributions to Mass Resolution

- Two components:
  - multiple scattering in the hadron absorber
    - dominant at low momentum
  - tracking accuracy
    - dominant at high momentum
- High mass dimuons (~3 GeV/c^2)
  - absorber does not matter
- Low mass dimuons (~1 GeV/c^2)
  - absorber is crucial
  - momentum measurement before the absorber promises huge improvement in mass resolution

➡ Track matching is critical for high resolution low mass dimuon measurements!



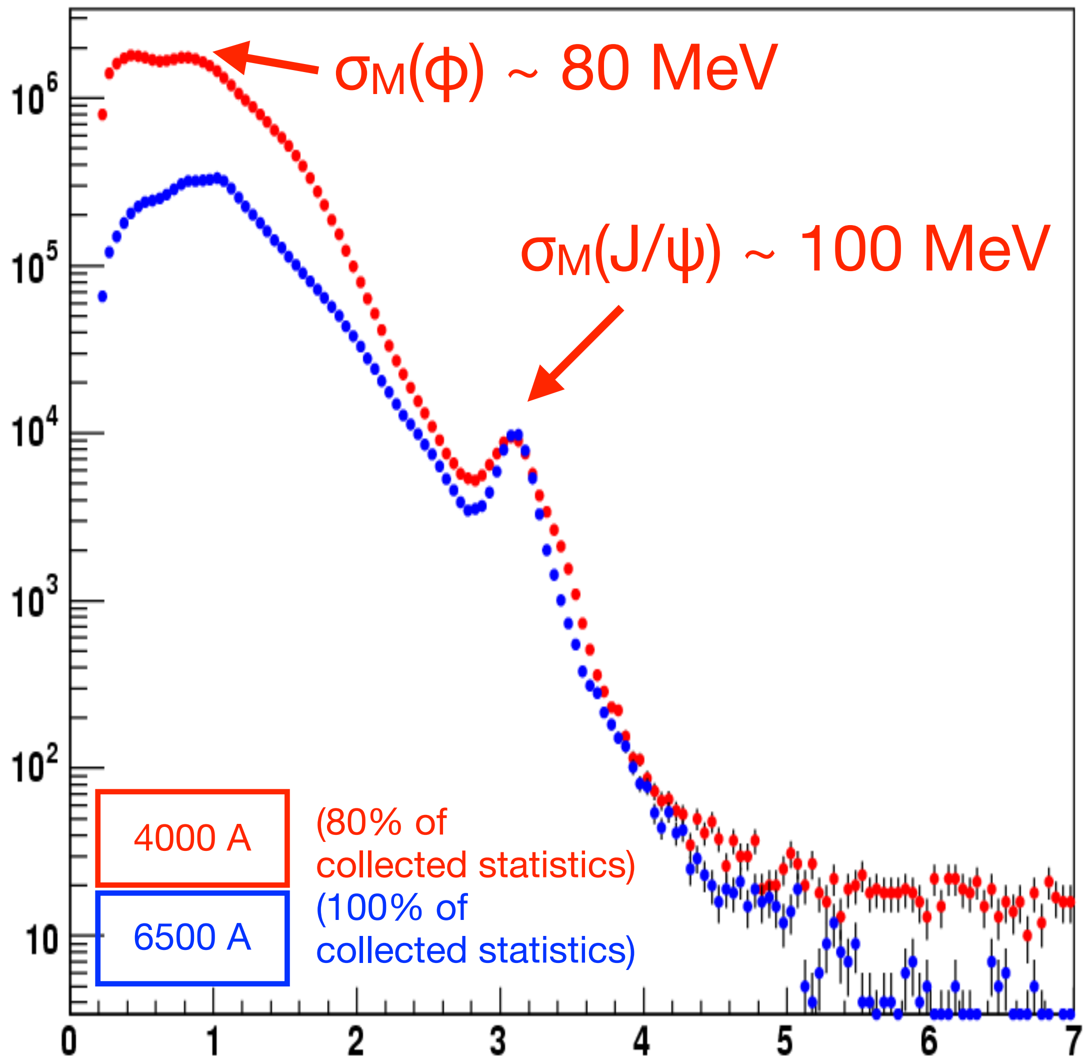
Muon Track Matching



- To be most effective: the track matching has to be done in
  - position space
  - momentum space

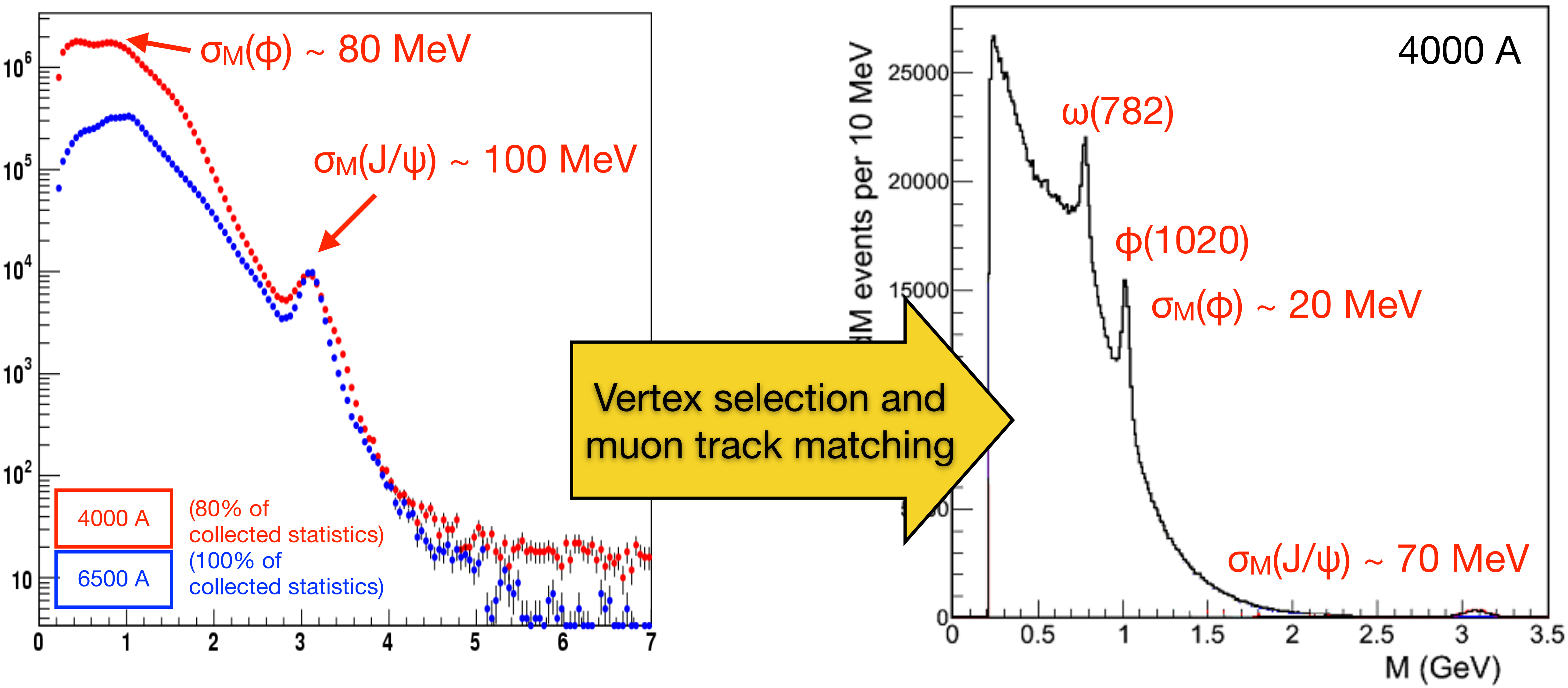
➡ The pixel telescope has to be a spectrometer!

Improvement in Mass Resolution



- Opposite sign dimuon mass distribution before quality cuts and without muon track matching

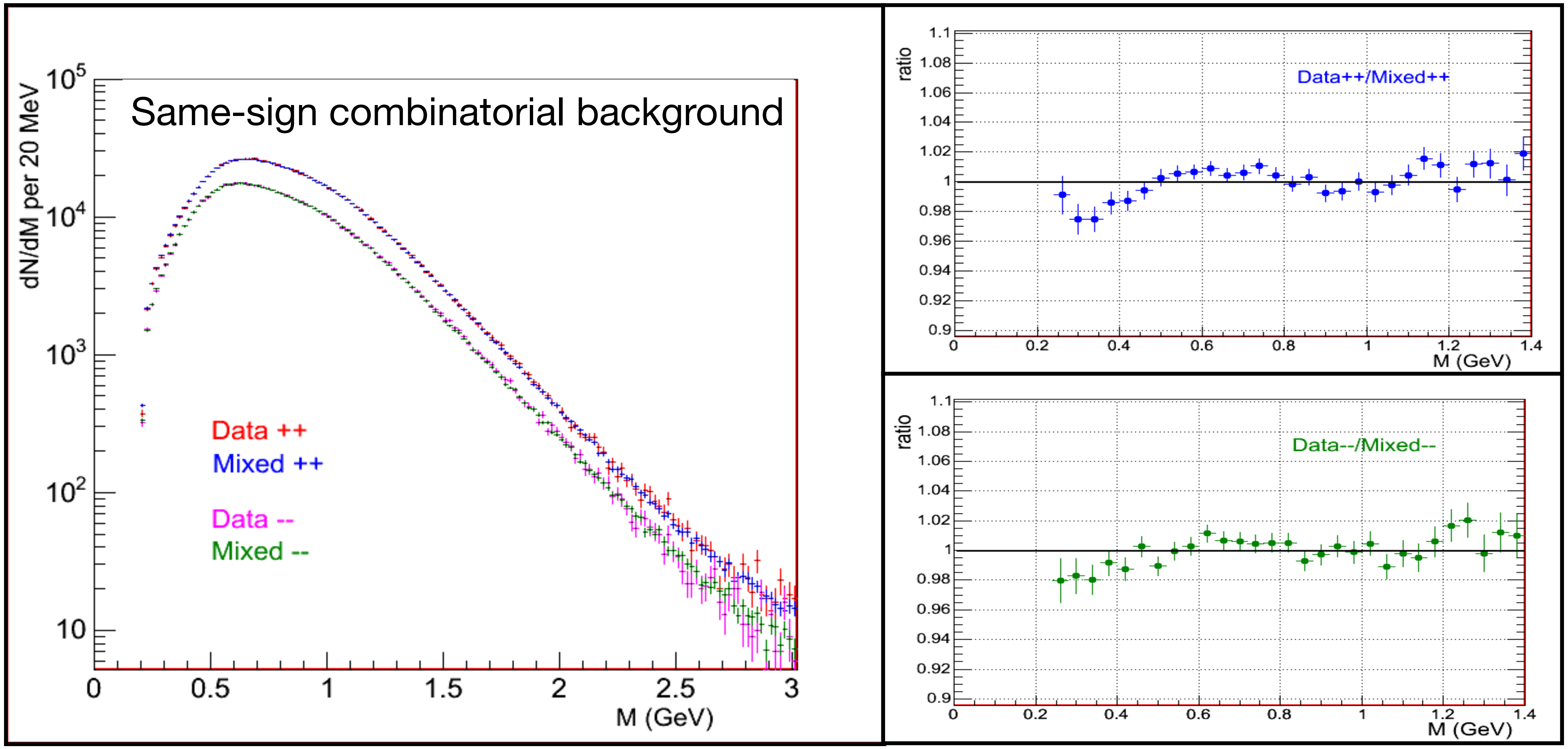
Improvement in Mass Resolution



- Opposite sign dimuon mass distribution before quality cuts and without muon track matching

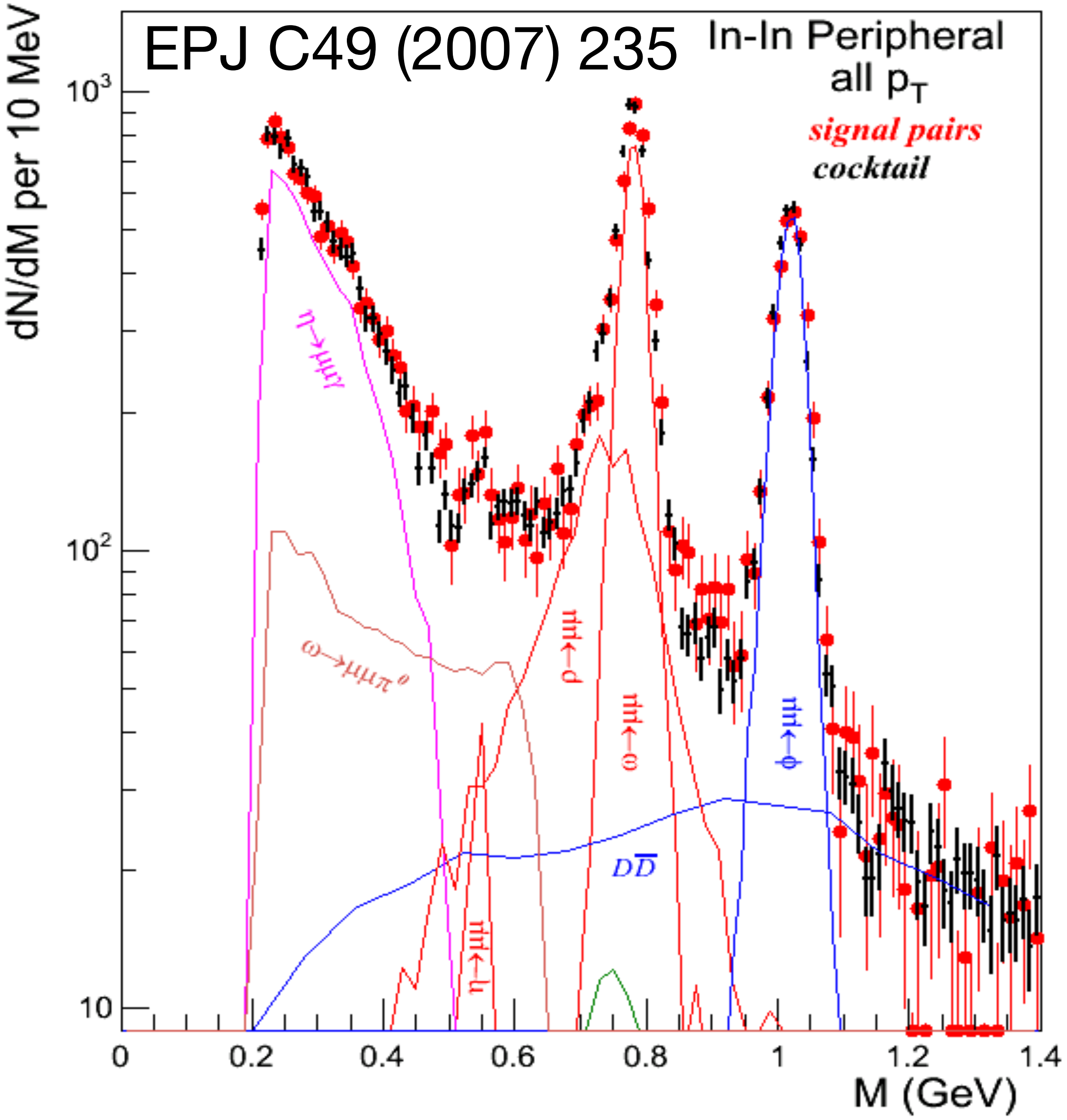
- Drastic improvement in mass resolution
- Still a large unphysical background

Event mixing: Same-sign Pairs

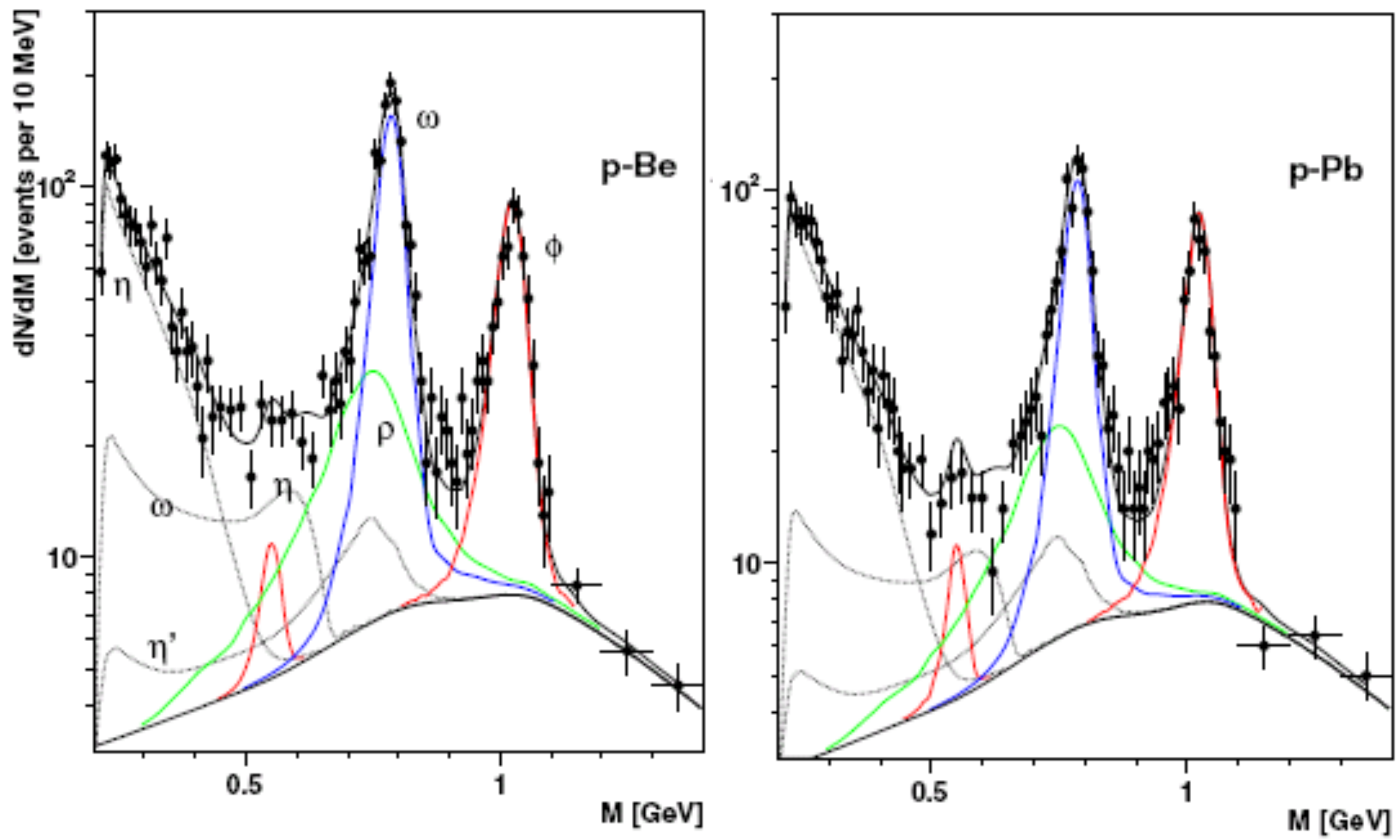


- Compare measured and mixed like-sign pairs
- Accuracy in NA60: ~1% over the full mass range

LMR in peripheral In-In Collisions



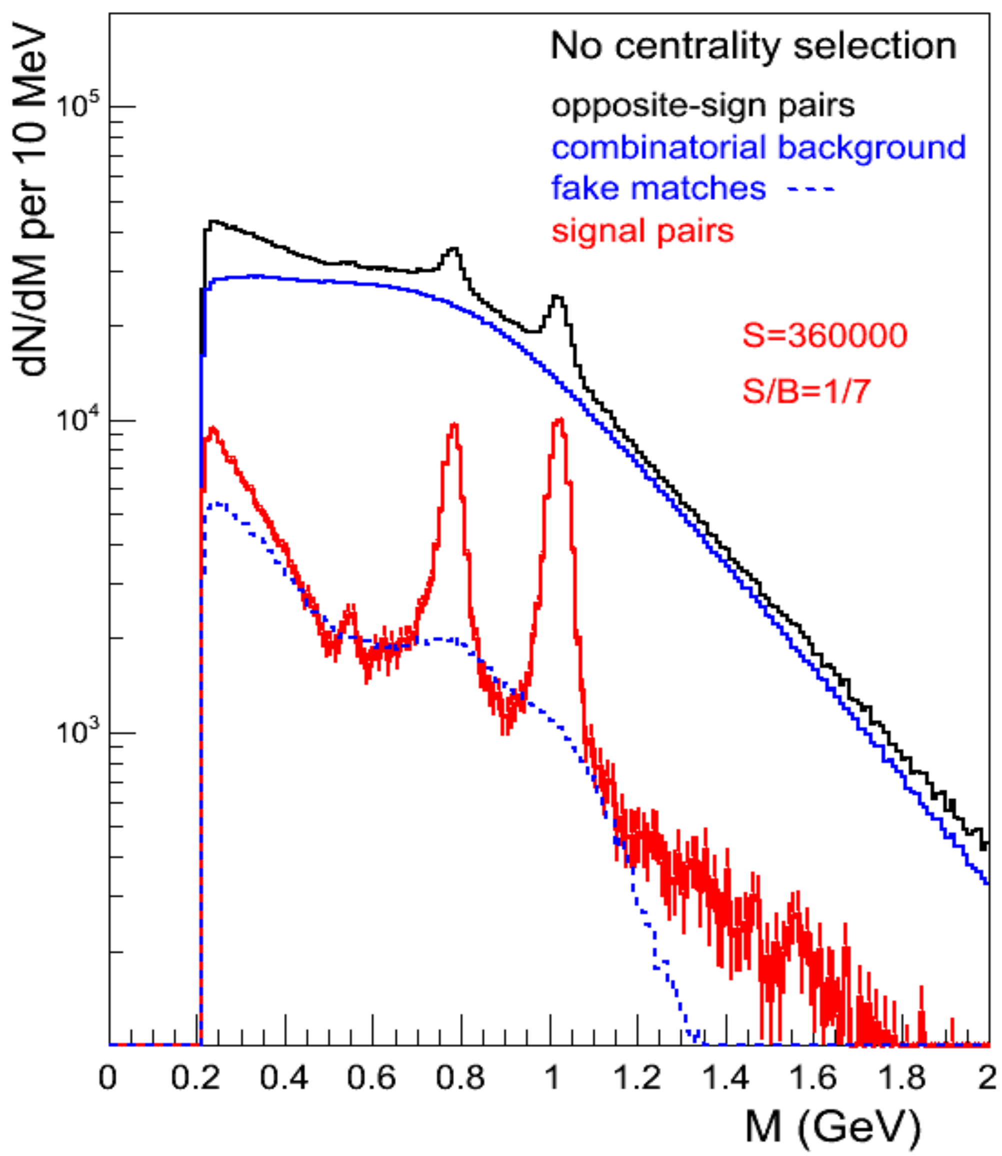
EPJ C43 (2005) 407

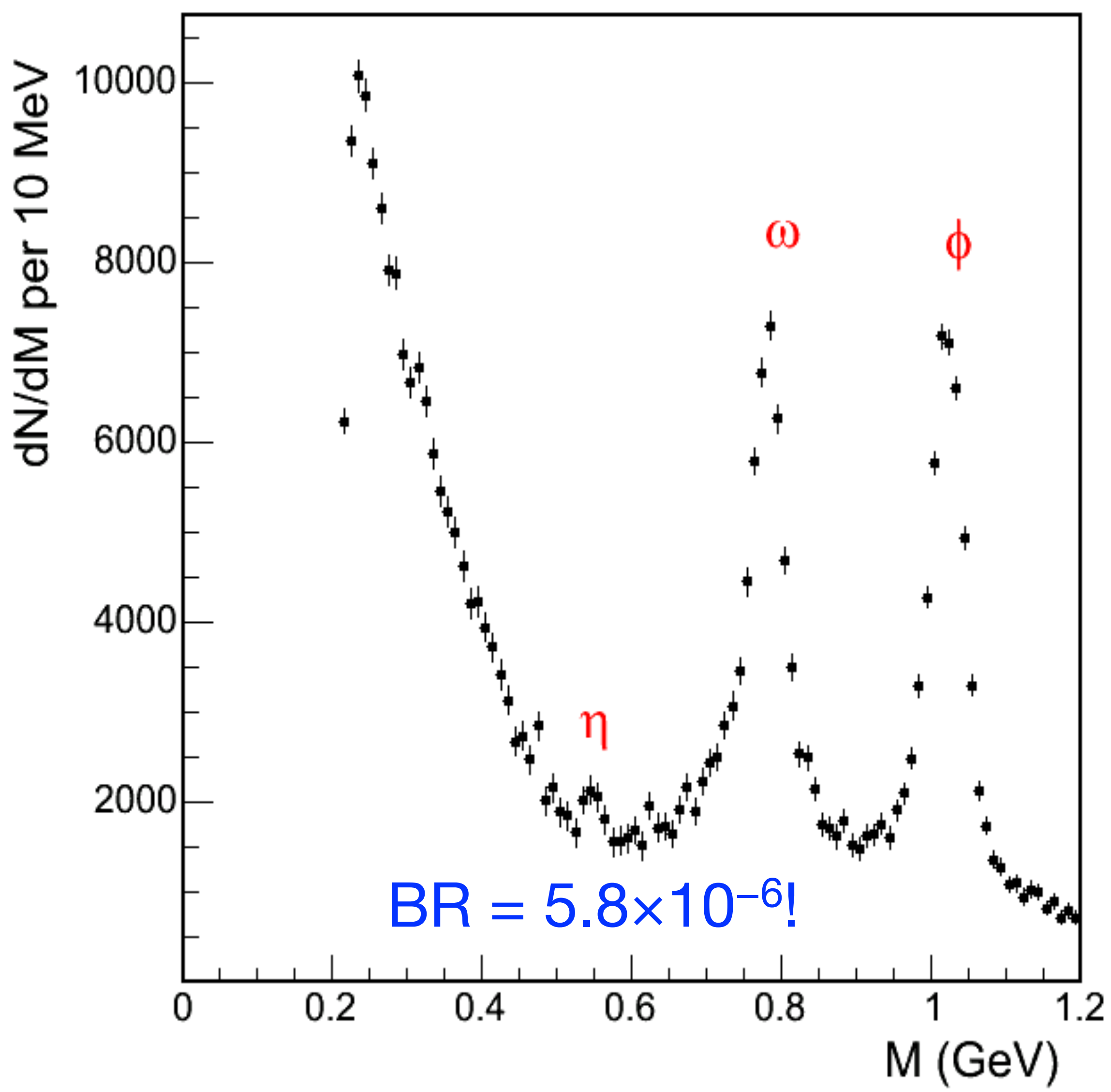


- Well described by meson decay ‘cocktail’: η, η’, ρ, ω, ϕ and DD contributions (Genesis generator developed within **CERES** and adapted for dimuons by **NA60**)
- Similar cocktail describes NA60 p-Be, In, Pb 400 GeV data

Part II

LMR in min. bias In-In Collisions





- Improvements:
  - Statistics
  - Resolution

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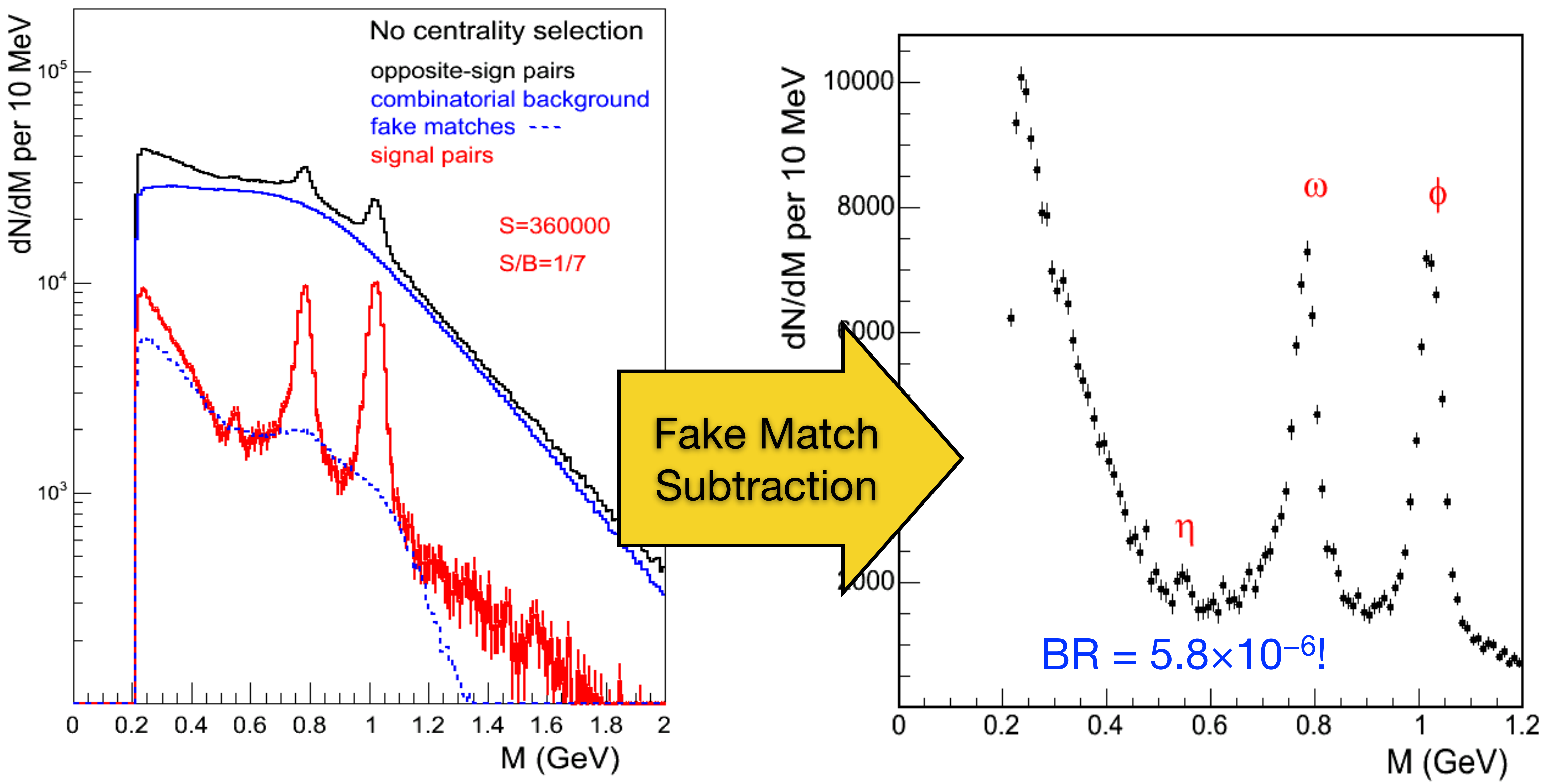
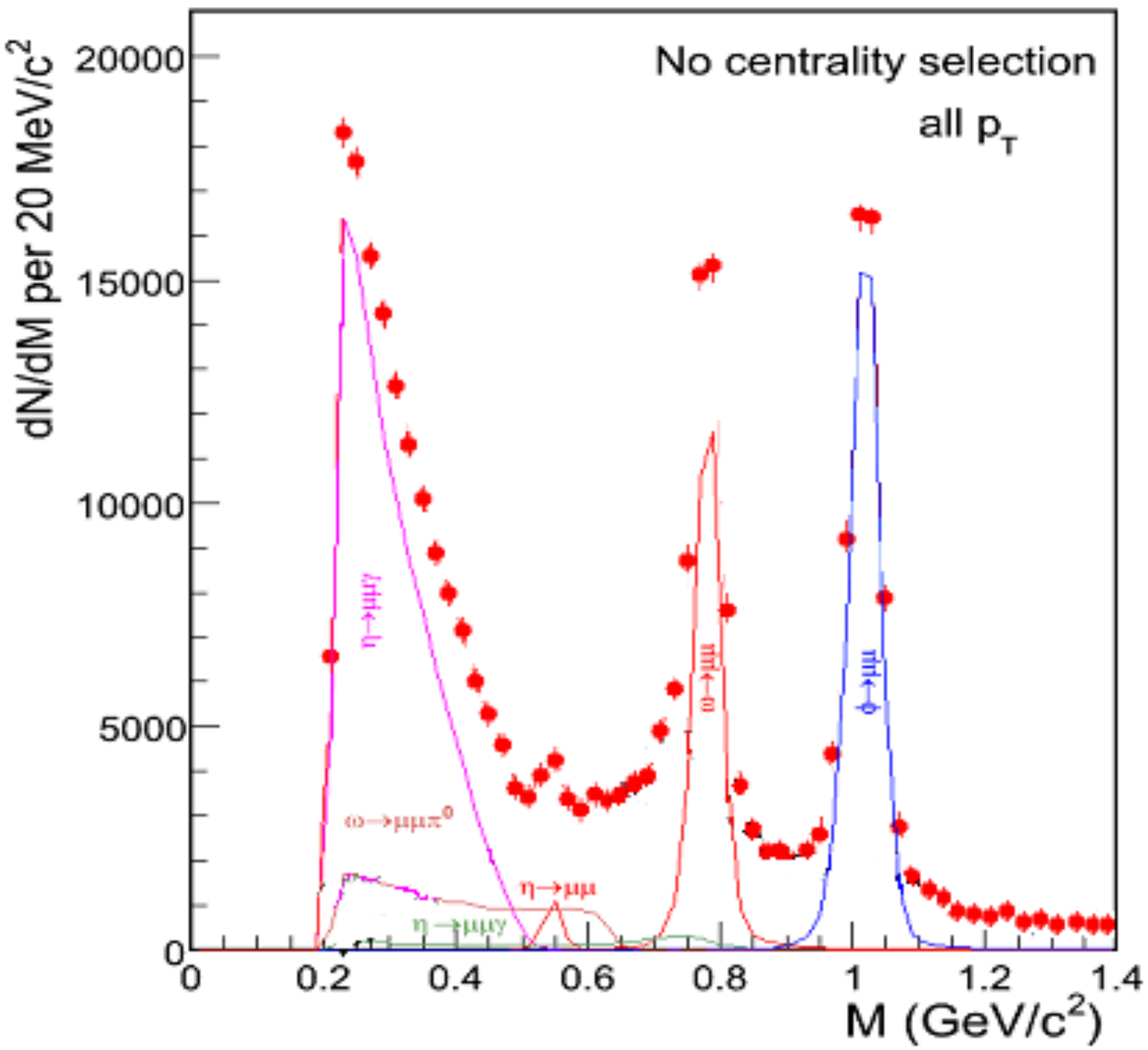


- Improvements:
  - Statistics
  - Resolution

Cocktail Subtraction

- How to nail down an unknown source?
  - Try to find excess above cocktail without fit constraints
- ρ:
  not subtracted/included in cocktail
- ω and ϕ:
  fix yields such as to get, after subtraction, a smooth underlying continuum
- η:
  (▼) set upper limit, defined by "saturating" the measured yield in the mass region close to 0.2 GeV (lower limit for excess)
  (△) use yield measured for $p_T > 1.4$ GeV/c



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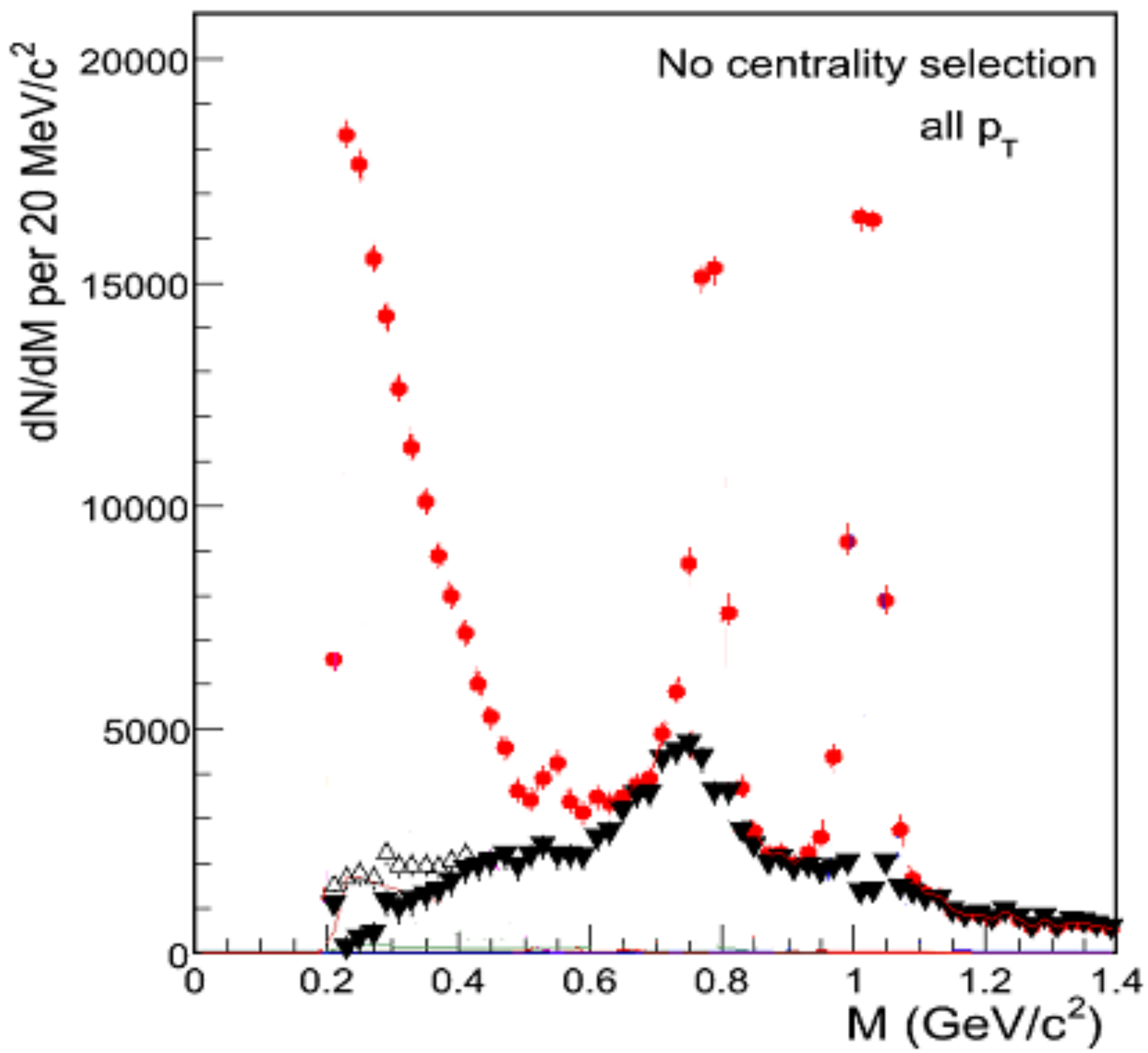
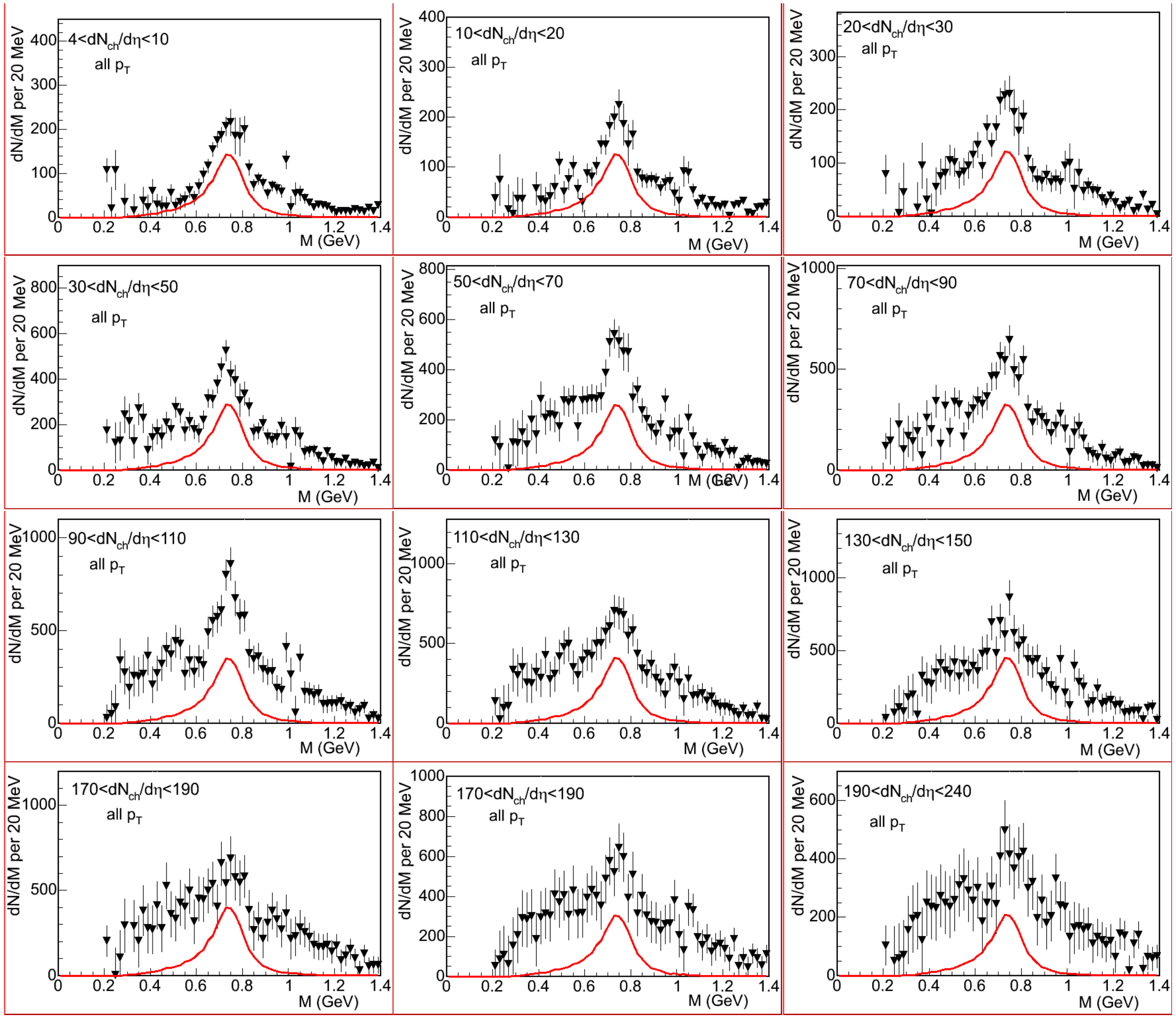


Excess Yield vs. Centrality

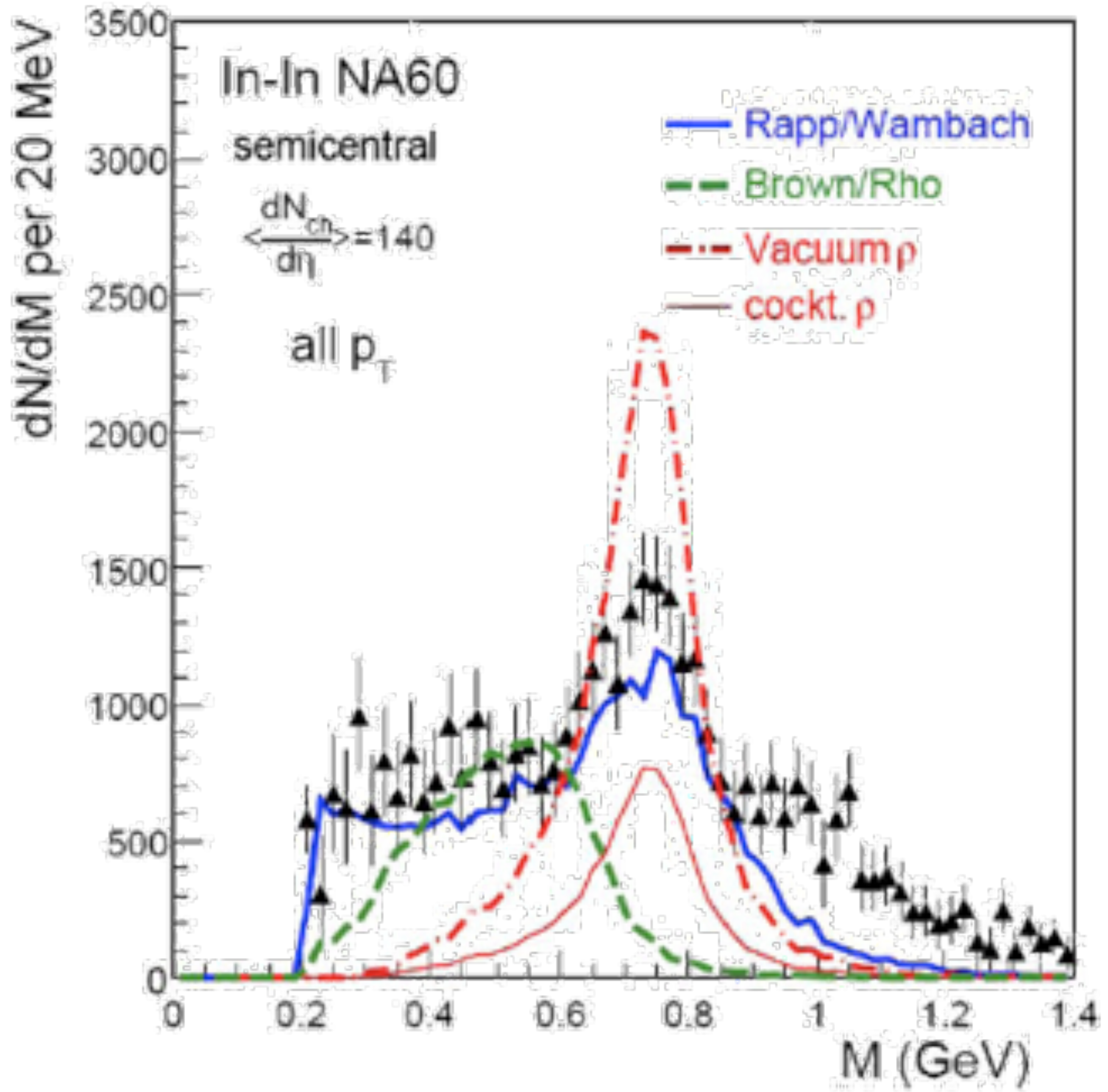
- data – cocktail (all p_T)
- No cocktail ρ and no DD subtracted
- Clear excess above the cocktail ρ, centred at the nominal ρ pole and rising with centrality
- Excess even more pronounced at low p_T



Model Comparison

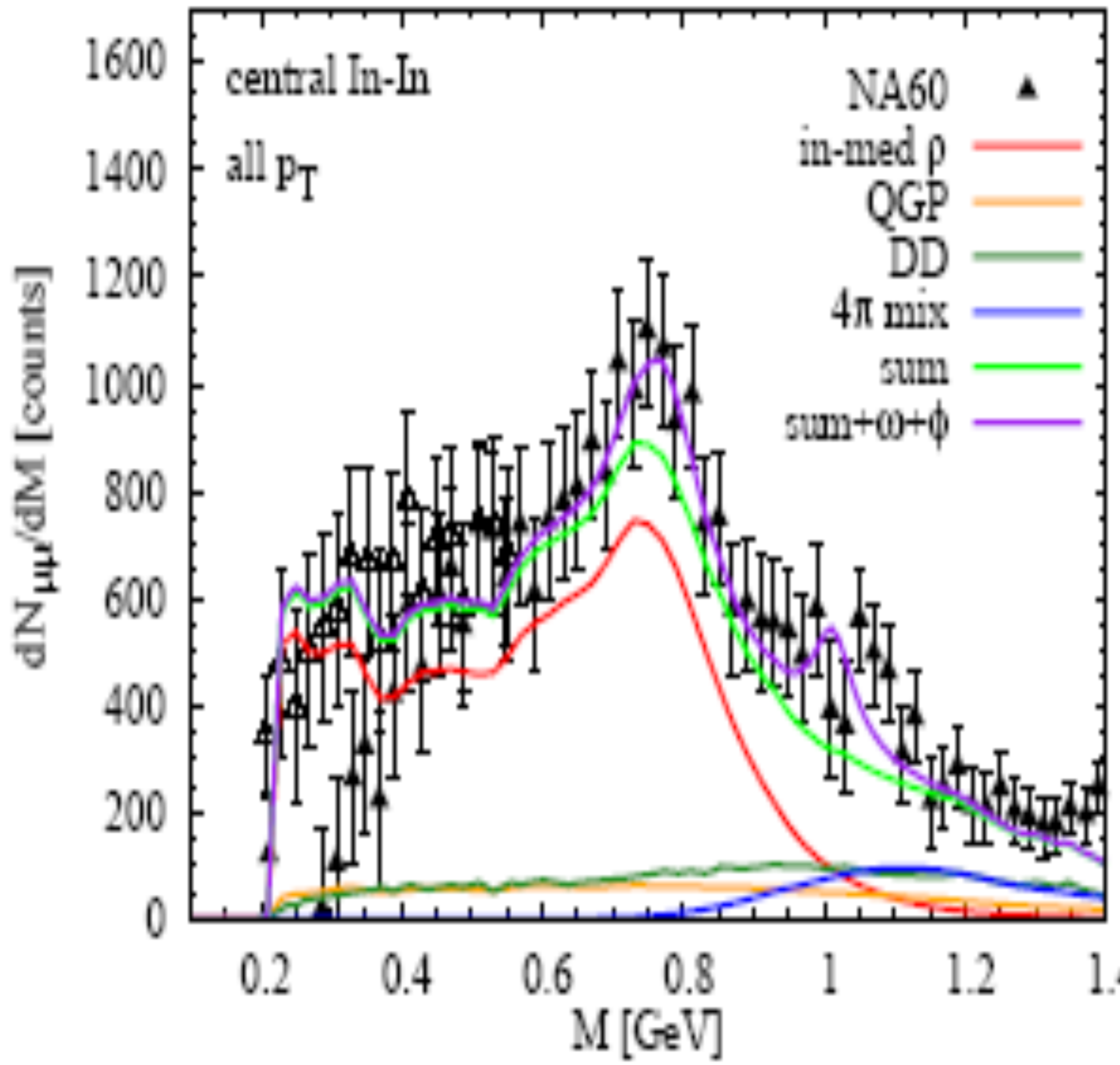
- Rapp & Wambach:
  - hadronic model with strong broadening but no mass shift
- Brown & Rho:
  - dropping mass due to dropping chiral condensate
- Calculations for all scenarios in In-In for $dN_{ch}/d\eta = 140$ (Rapp et al.)
- Spectral functions after acceptance filtering, averaged over space-time and momenta
- Keeping original normalization

➡ Data consistent with broadening of ρ (RW), mass shift (BR) not needed

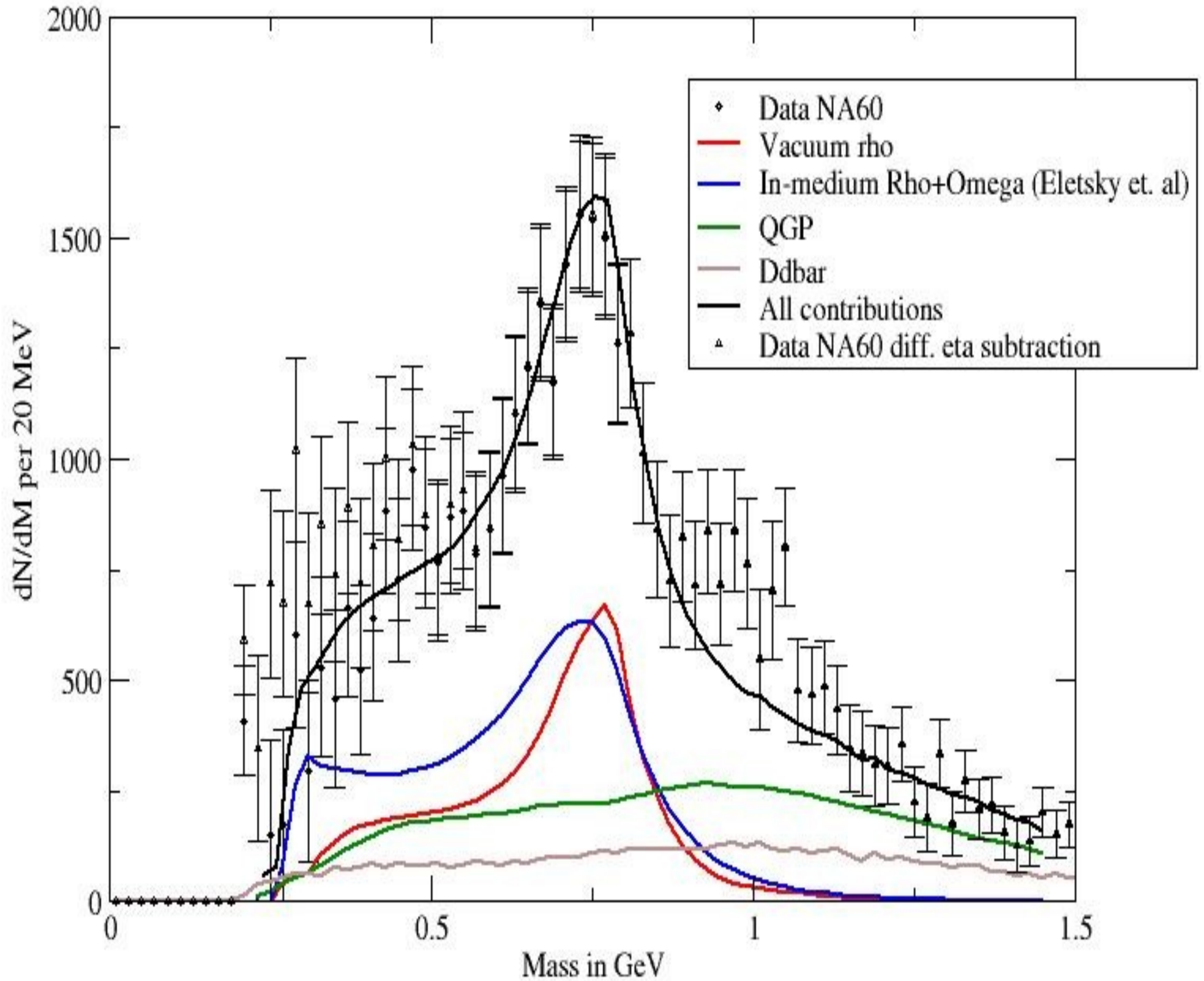


Towards Higher Masses (M>1 GeV/c^2)

Rapp/van Hees



Ruppert/Renk

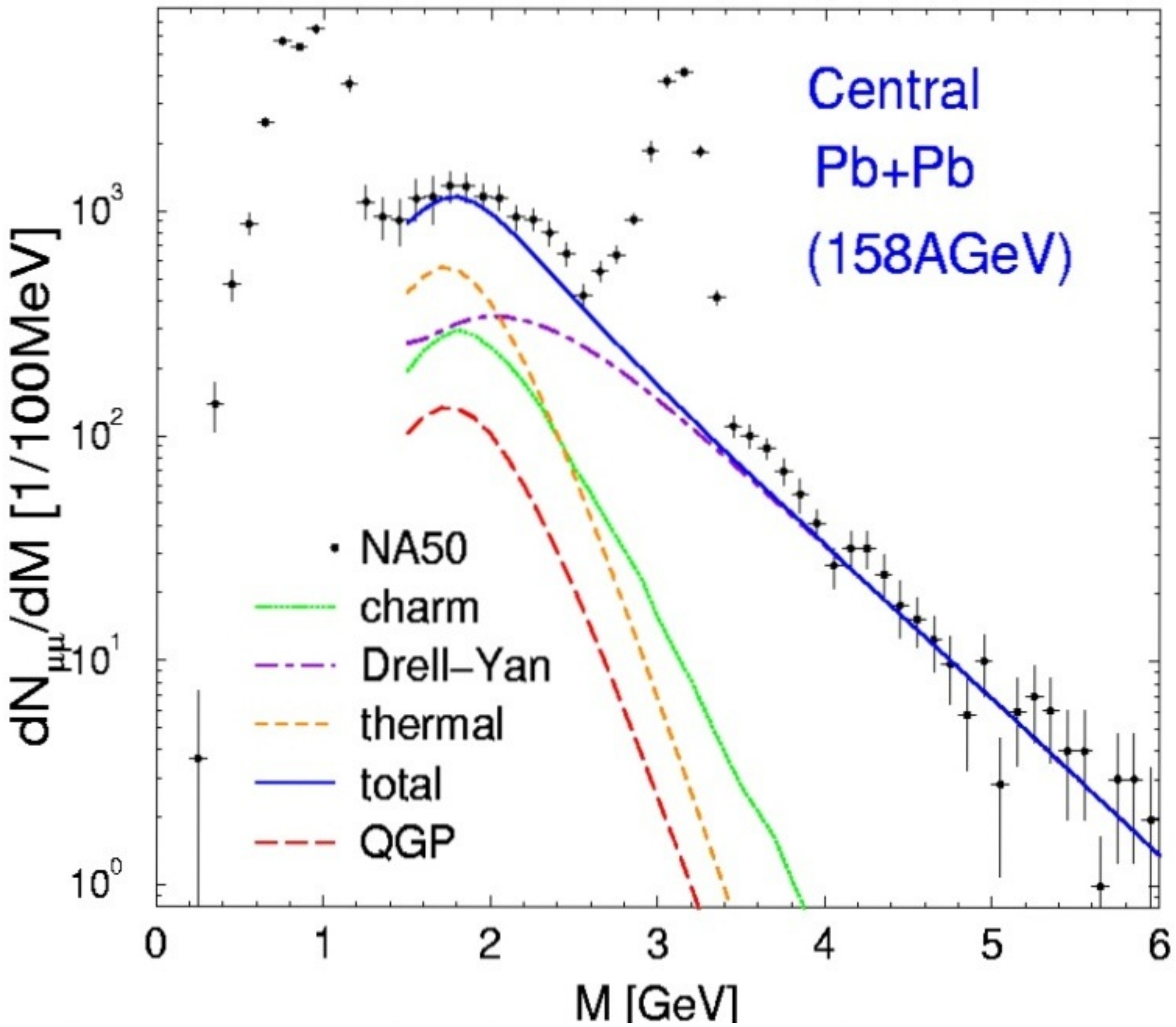


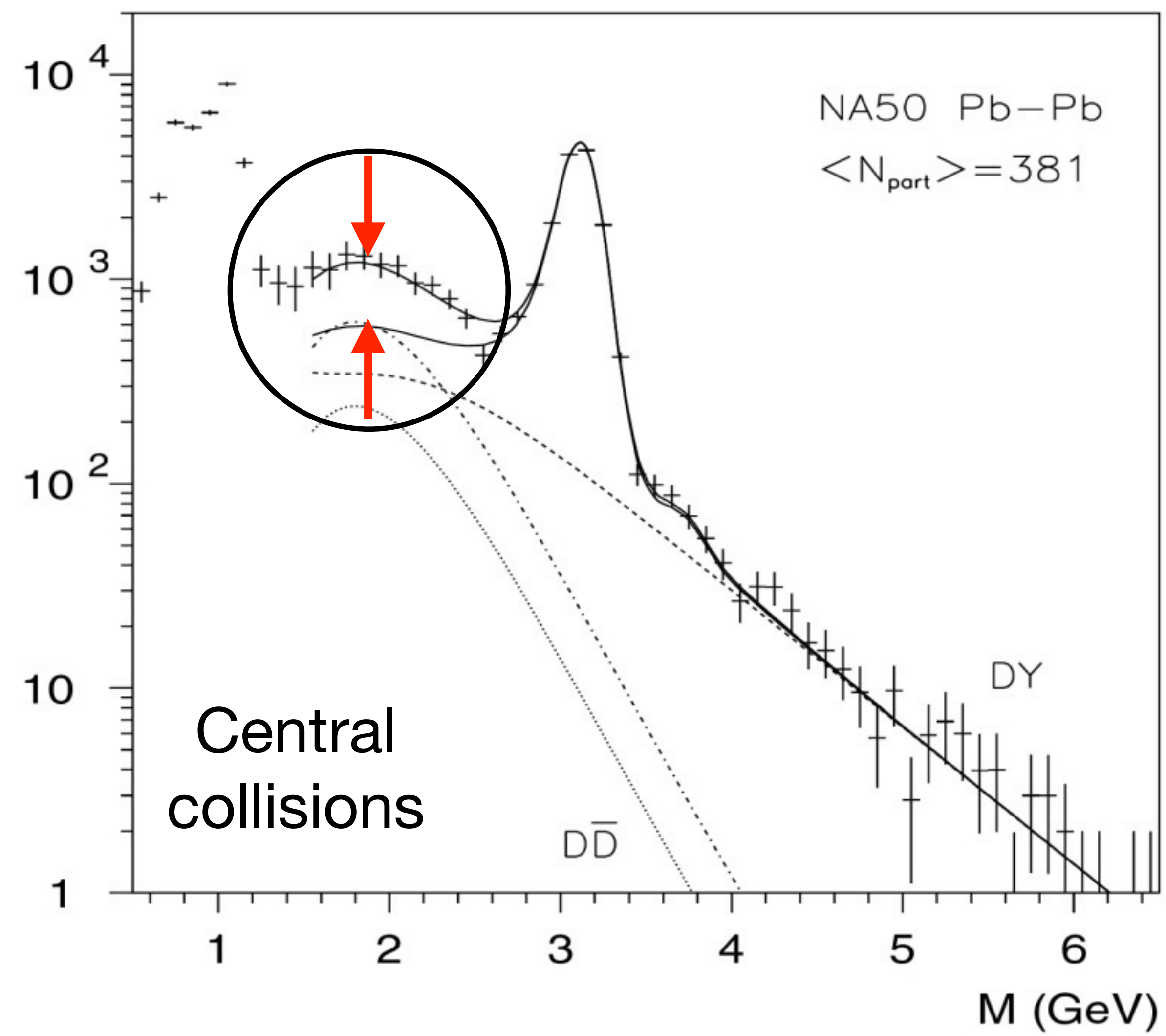
Hadron-Parton Duality

- Dominant at high M:
  - Hadronic processes
  - 4π …

- Dominant at high M:
  - Partonic processes
  - Mainly q-$\bar{q}$ annihilation

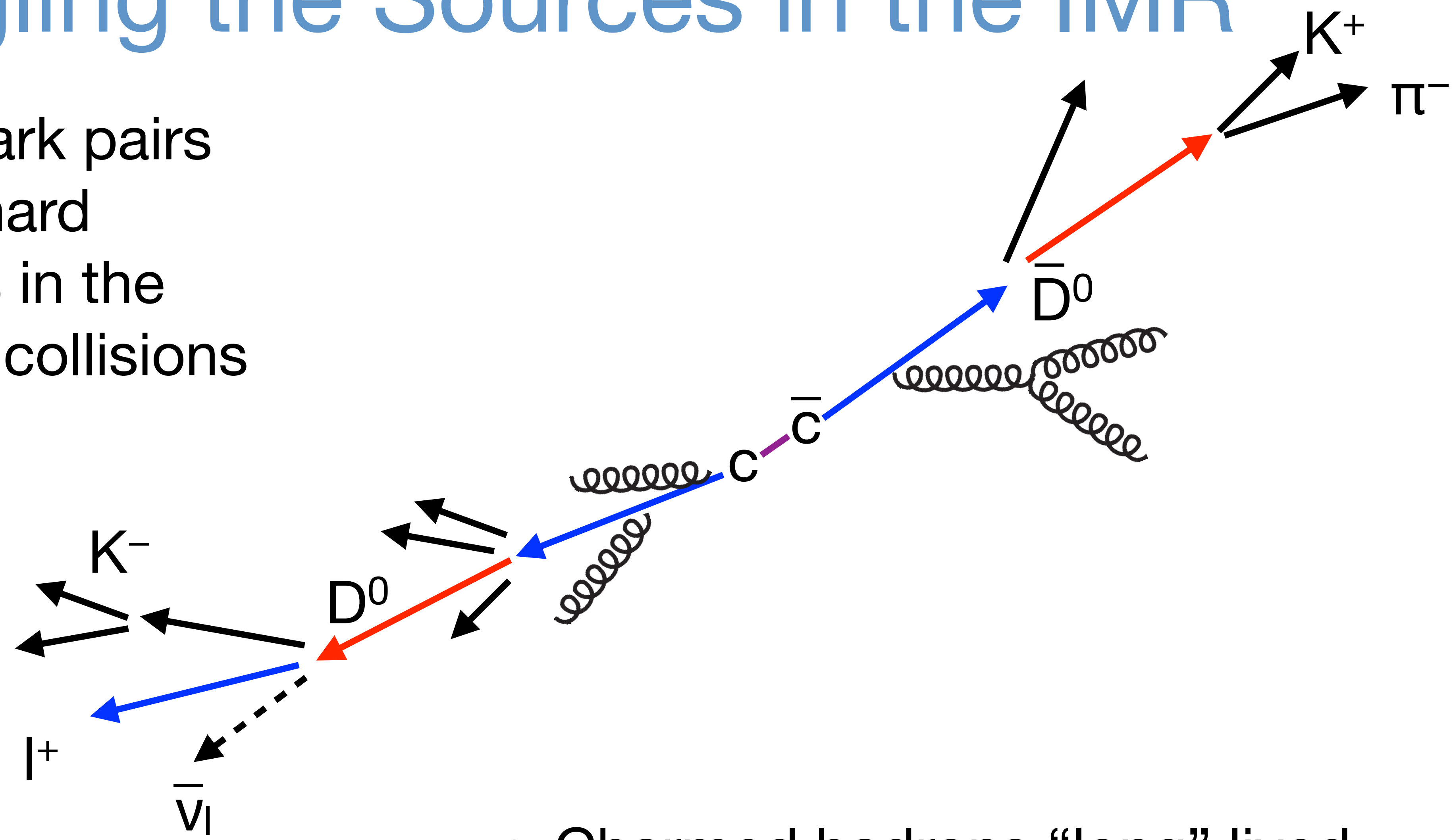
Intermediate Mass Region (IMR)



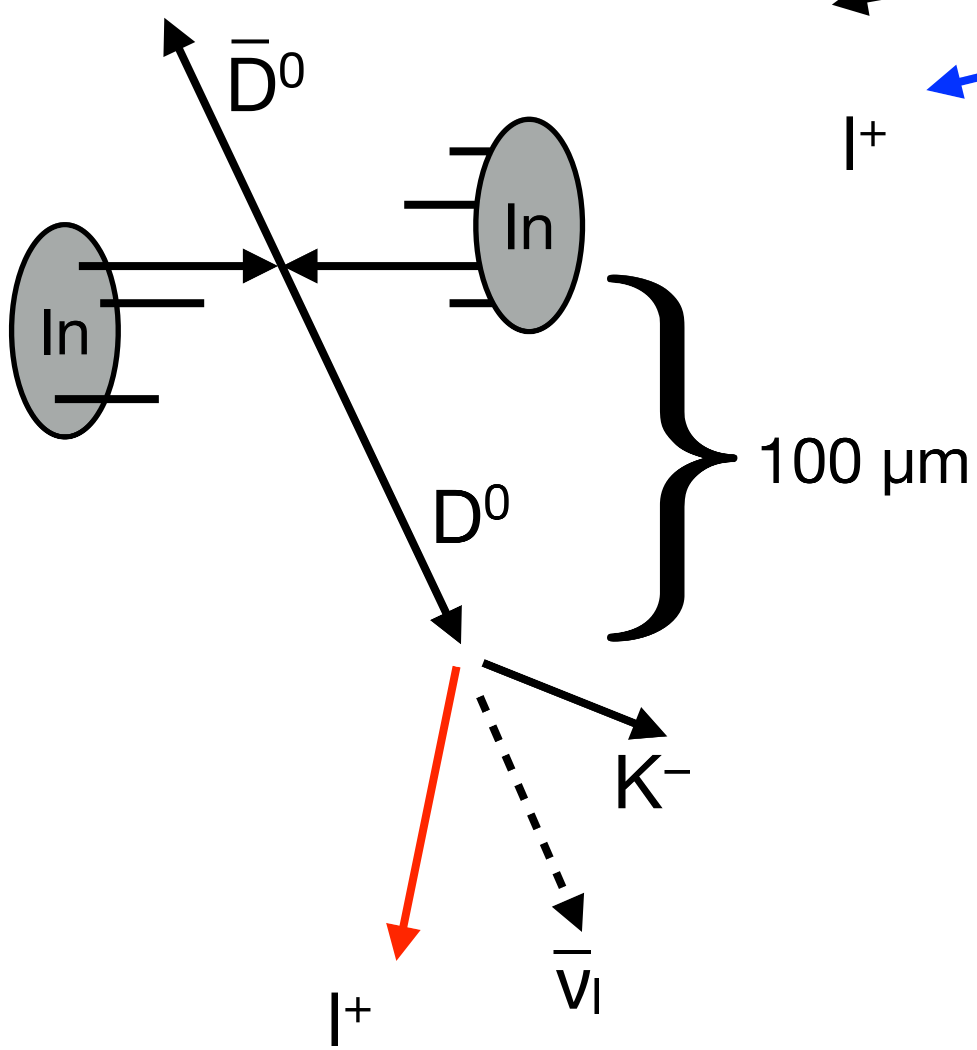


- NA50: excess observed in IMR in central Pb-Pb collisions
  - Charm enhancement?
  - Thermal radiation?
- Answering this question was one of the main motivations for building NA60

Disentangling the Sources in the IMR



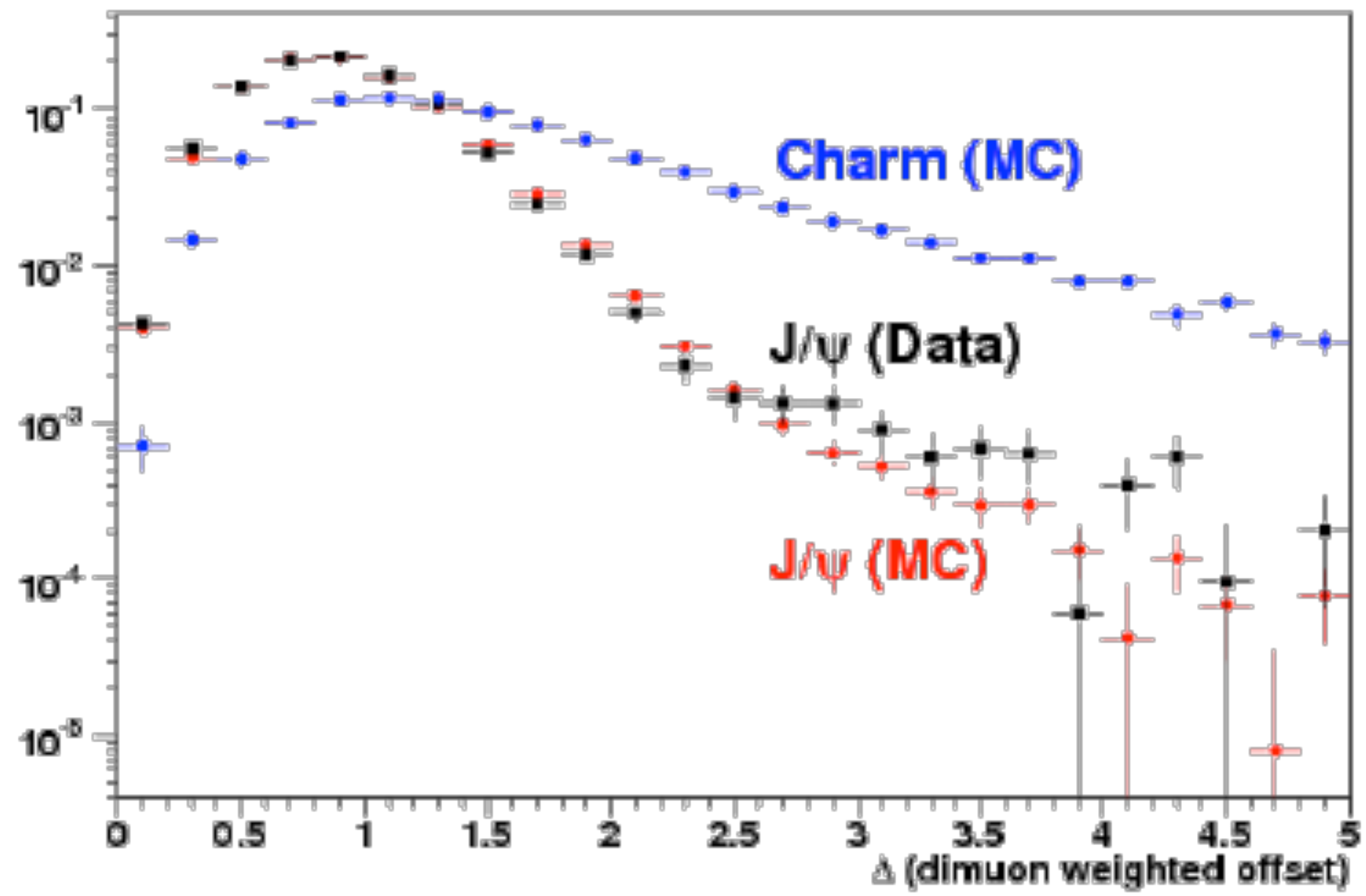
- Charm quark-antiquark pairs mainly produced in hard scattering processes in the earliest phase of the collisions



- Charmed hadrons “long” lived → identify typical offset (“displaced vertex”) of D-meson decays (~100 μm)
- Need superb vertexing accuracy (20–30 μm in the transverse plane)
  → NA60

How well does it work?

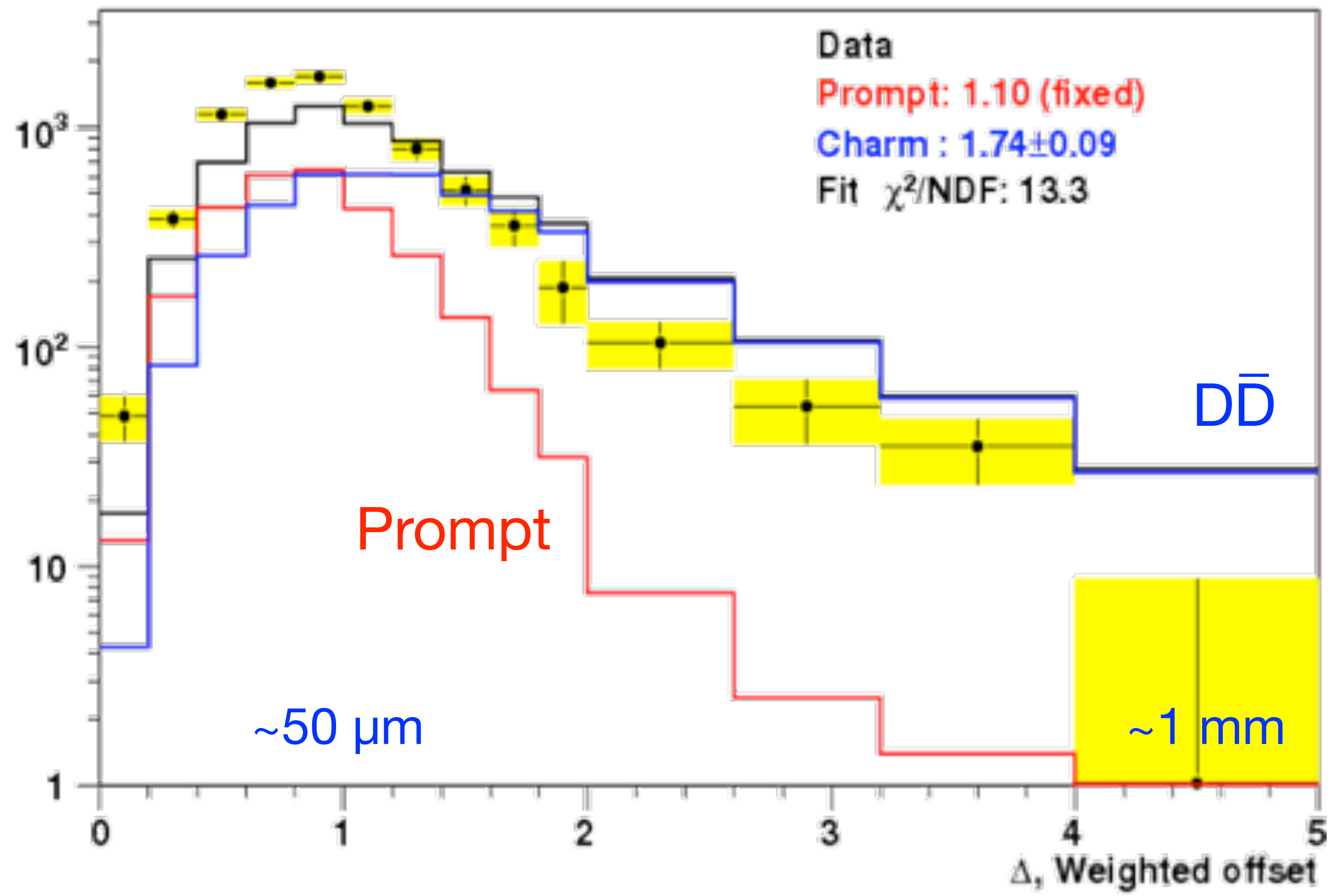
- Measure for vertex displacement
  - primary vertex resolution
  - momentum dependence of secondary vertex resolutions
  - ➡ “dimuon weighted offset”
- Charm decays (D mesons) → displaced
- J/ψ → prompt
- Vertex tracking under control!



IMR excess: charm enhancement?

- Approach:
  - fix the prompt contribution to the expected Drell-Yan yield
  - check whether the offset distribution is consistent with charm

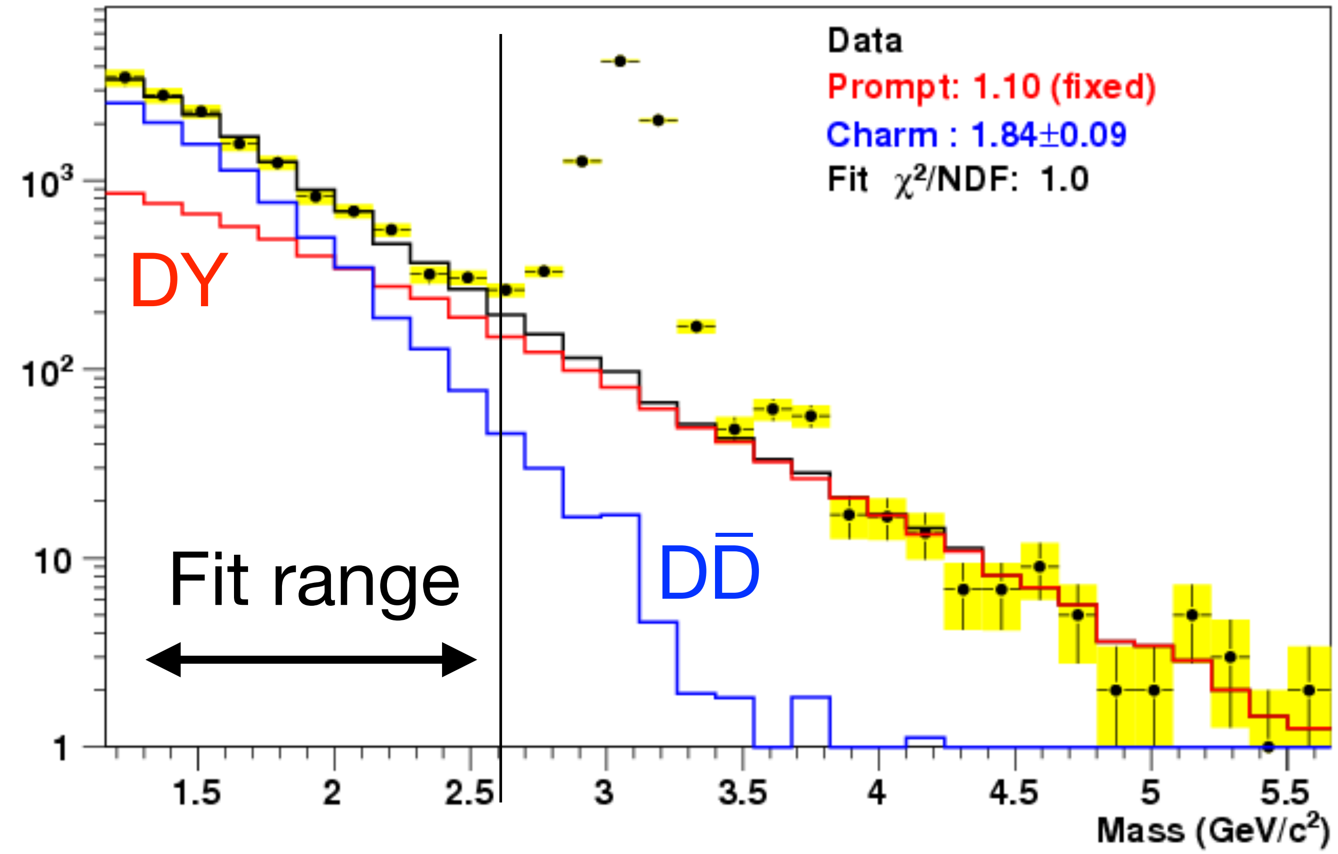
EPJ C 59 (2009) 607

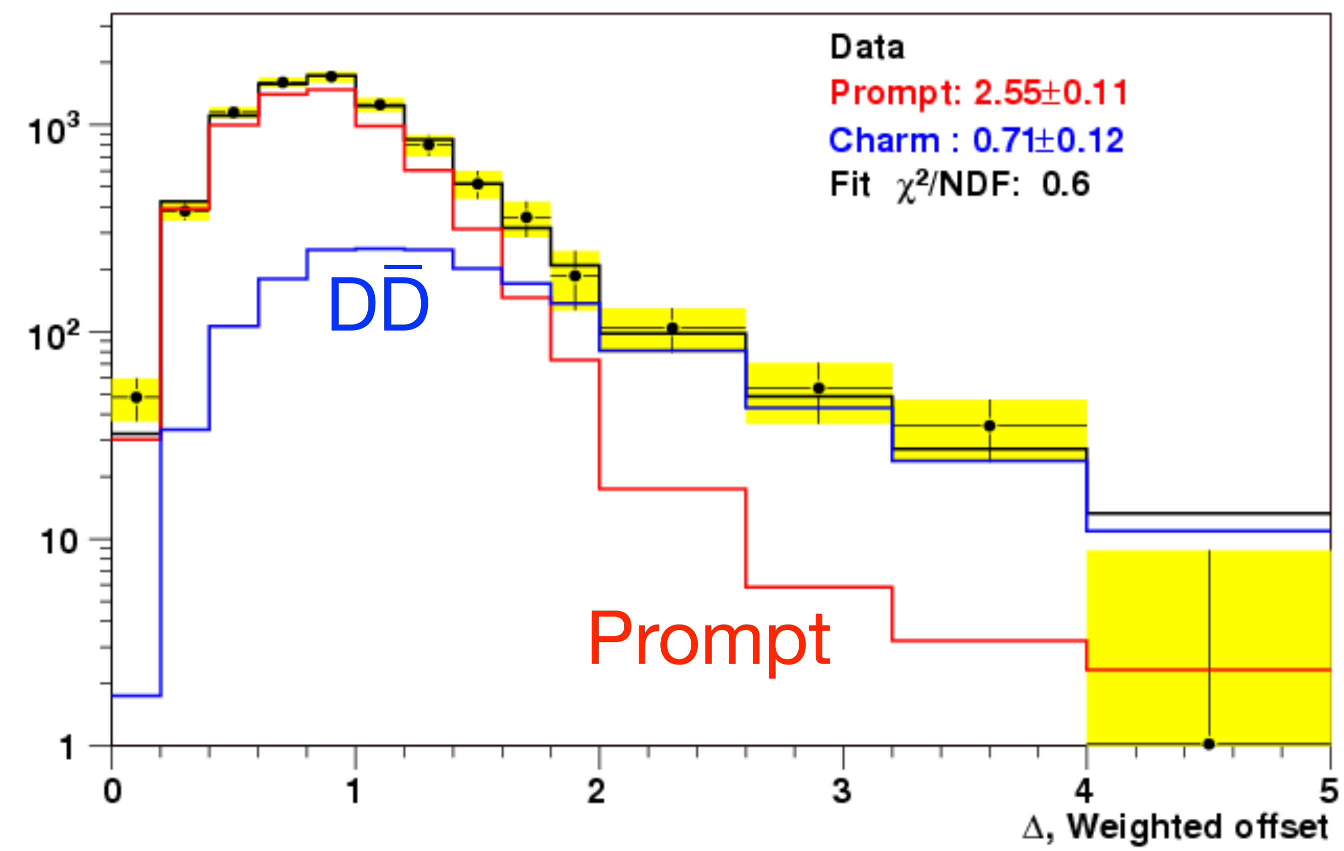


- Charm cannot describe the small offset region!

How many prompt pairs are needed?

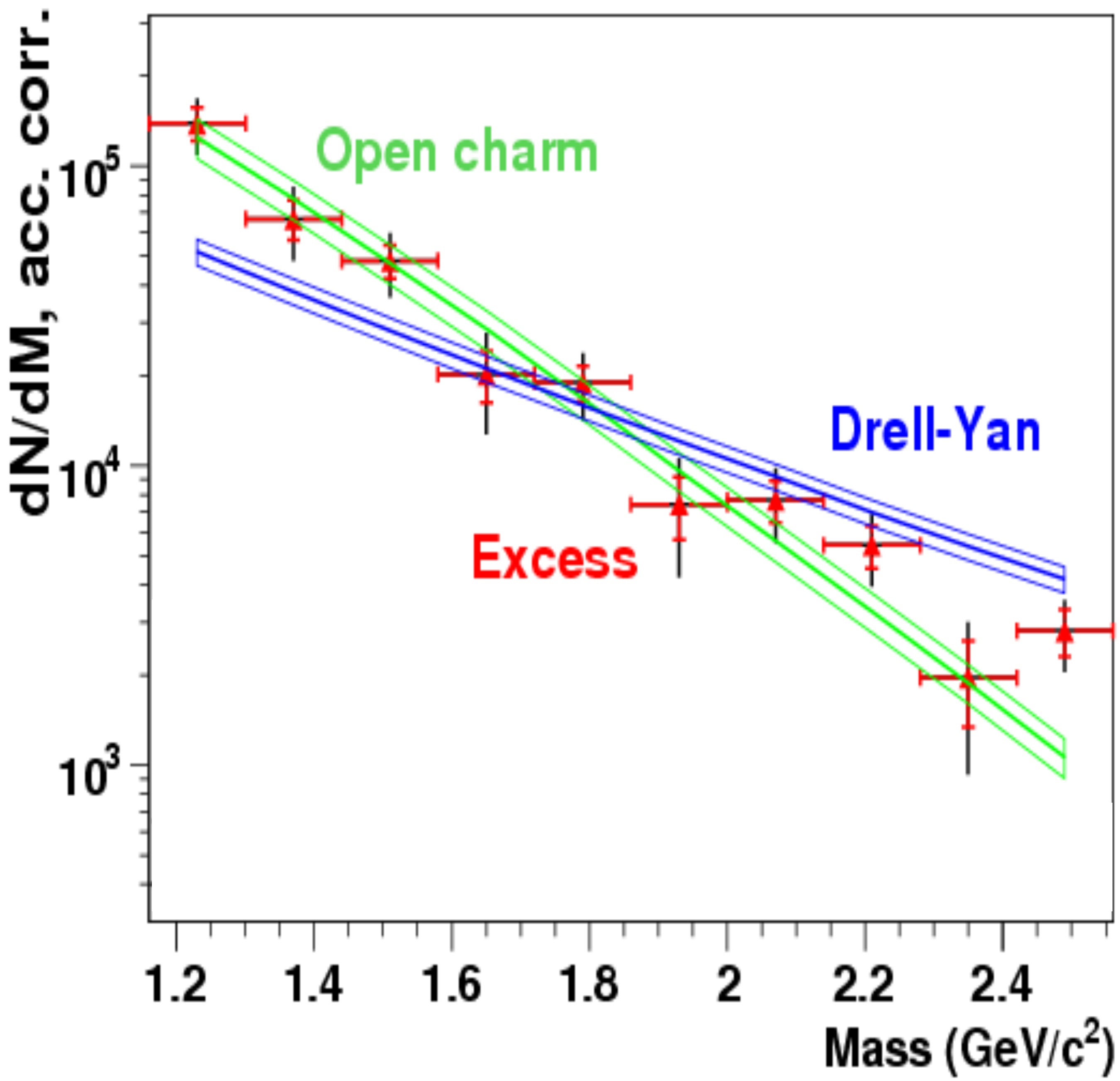
- Approach:
  - fit offset distribution with both charm and prompt contributions as free parameters
- Prompt component:
  - ~2.3 times larger than Drell-Yan contribution
- Charm component:
  - ~70% of the yield extrapolated from NA50's p-A data





Decomposition of Mass Spectrum

- IMR: $1.16 < M < 2.56$ GeV/c^2 (between φ and J/ψ)
- Definition of excess:
  - excess = signal − [Drell-Yan (1.0 ± 0.1) + Charm (0.7 ± 0.15)]

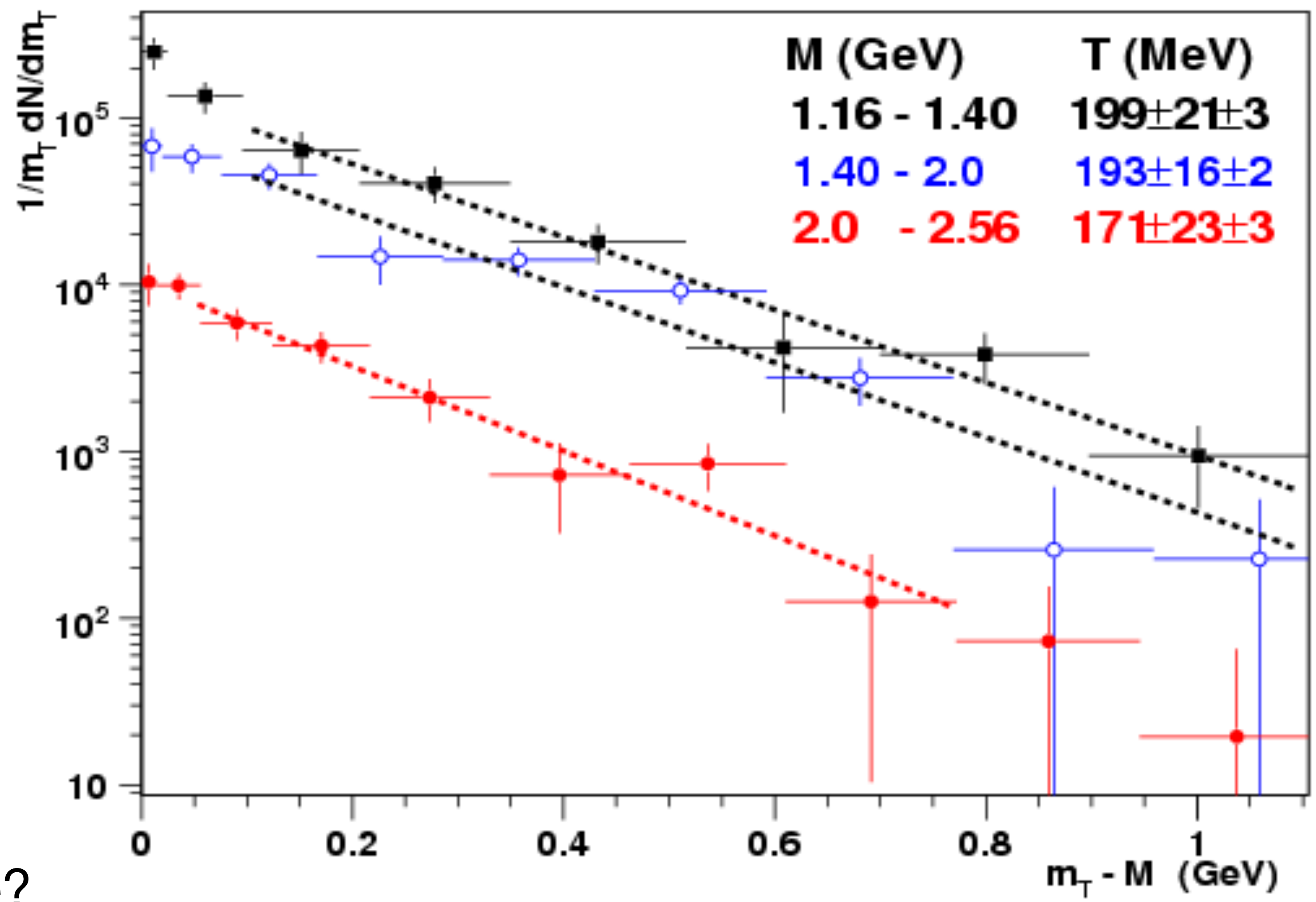


More detailed look at p_T dependence

- Investigate excess in different mass regions as function of m_T
  - fit with exponential function (shown for IMR)
  - extract T_{eff} slope parameter

$$m_T = \sqrt{p_T^2 + M^2}$$

$$\frac{dN}{m_T\, dm_T} \propto \mathrm{e}^{-m_T/T_{\mathrm{eff}}}$$



- $\langle T_{eff} \rangle \approx 190$ MeV
  - is this related to temperature?
  - if so, this is close to the critical temperature at which the QCD phase transition occurs

Interpretation of T_{eff}

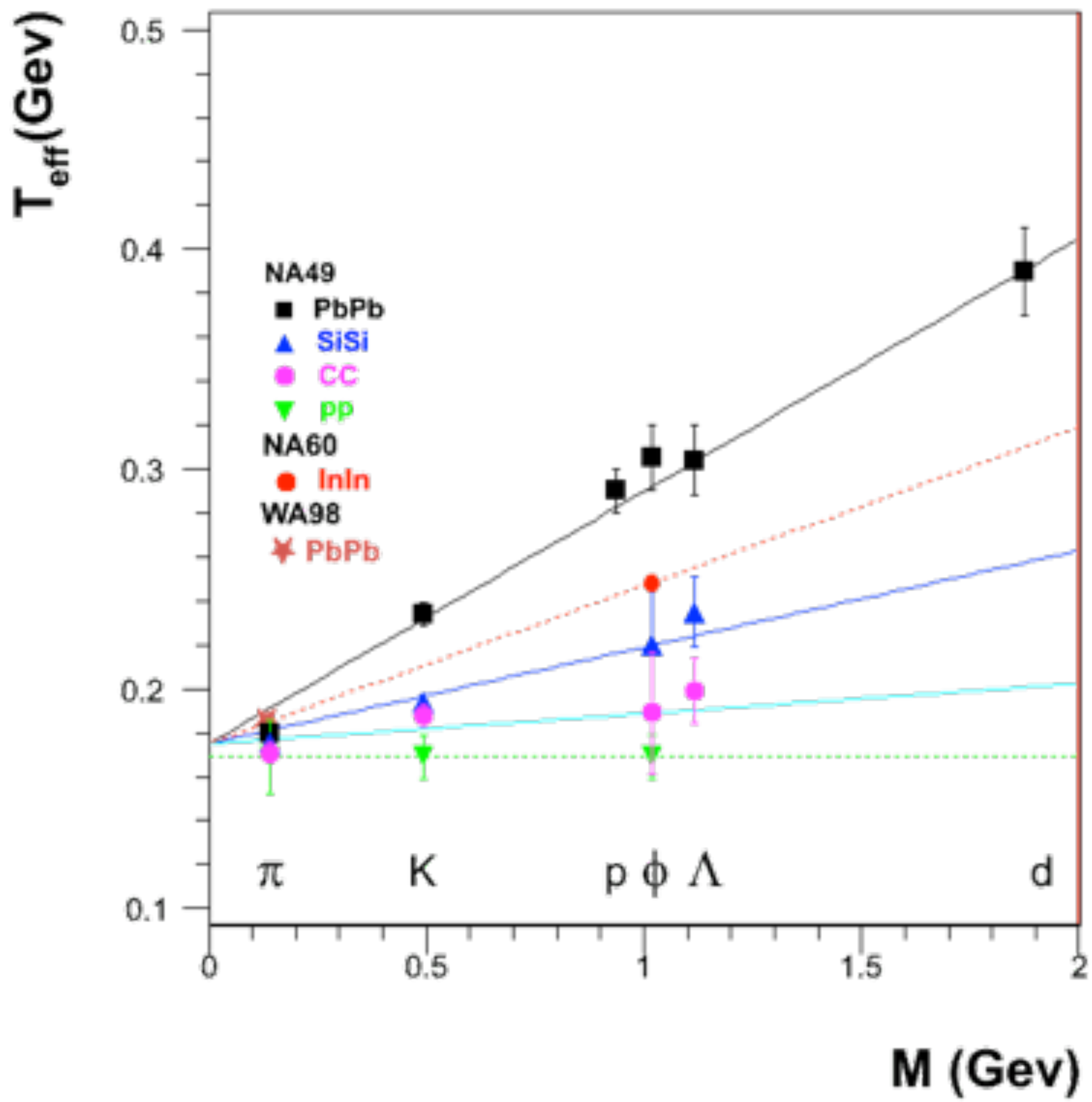
- Interpretation of T_{eff} from fitting to $\exp(-m_T/T_{eff})$
  - Static source: T_{eff} interpreted as the source temperature
  - Radially expanding source:
    - T_{eff} reflects temperature and flow velocity
    - T_{eff} depends on the m_T range
    - High-p_T limit: $T_{\rm eff} = T_f \sqrt{\frac{1+v_T}{1-v_T}} \quad p_T \gg m$ (common to all hadrons)
    - Low-p_T limit: $T_{\rm eff} \approx T_f + \frac{1}{2} m \langle v_T^2 \rangle \quad p_T \ll m$ (mass ordering of hadrons)
- Final spectra: space-time history $T_i \rightarrow T_{fo}$ & emission time
  - Hadrons
    - interact strongly
    - freeze out at different times depending on cross section with pions
    - T_{eff} → temperature and flow velocity at thermal freeze out
  - Dileptons
    - do not interact strongly
    - decouple from medium after emission
    - T_{eff} → temperature and velocity evolution averaged over emission time

Mass ordering of hadronic slopes

- Separation of thermal and collective motion
- Reminder
  - blast wave fit to all hadrons simultaneously
- Simplest approach

$$T_{\text{eff}} \approx T_f + \frac{1}{2} m \langle v_T^2 \rangle \quad p_T \ll m$$

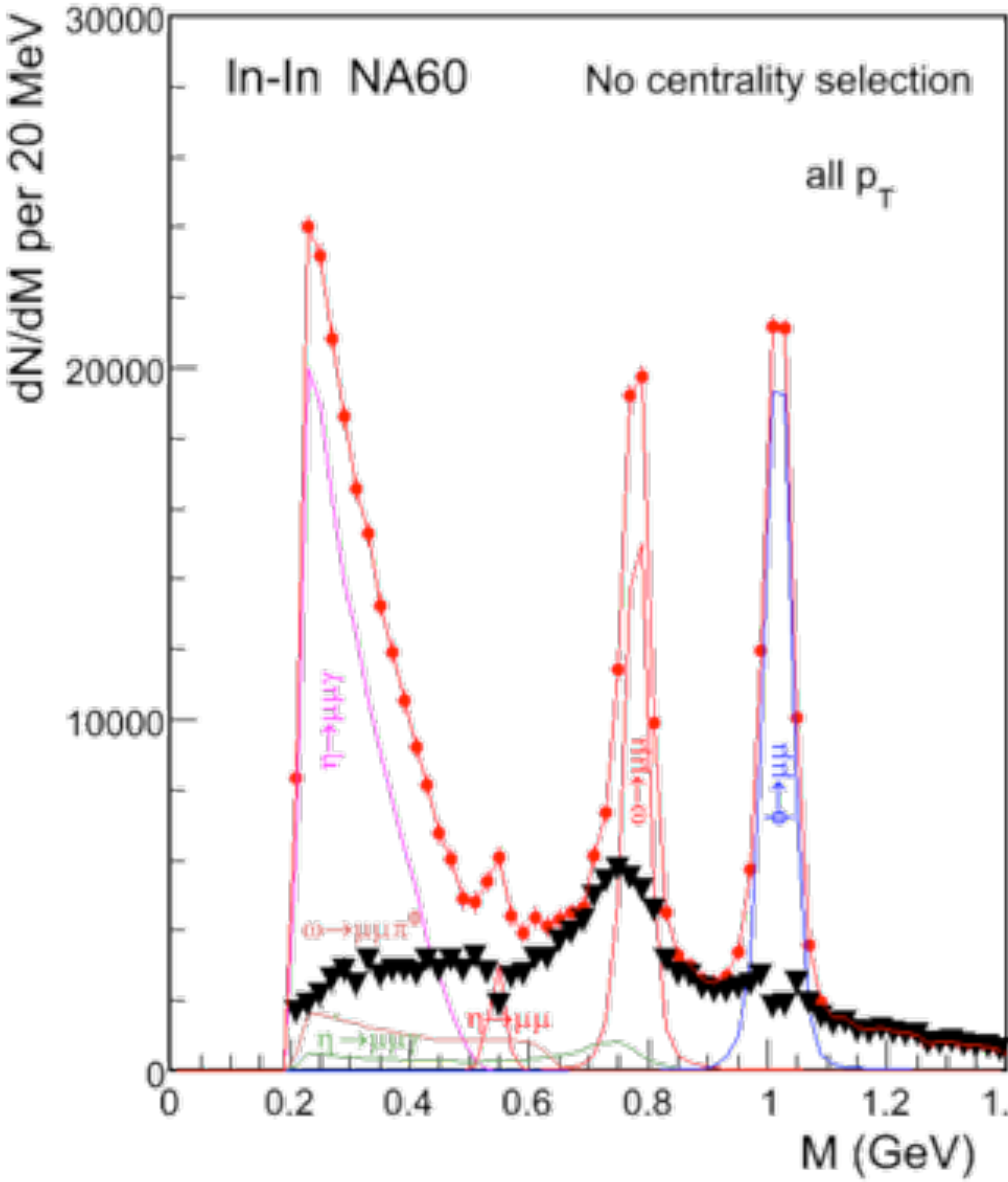
  - slope of $\langle T_{\text{eff}} \rangle$ vs. m is related to radial expansion
  - baseline is related to thermal motion
- Works (at least qualitatively) at SPS



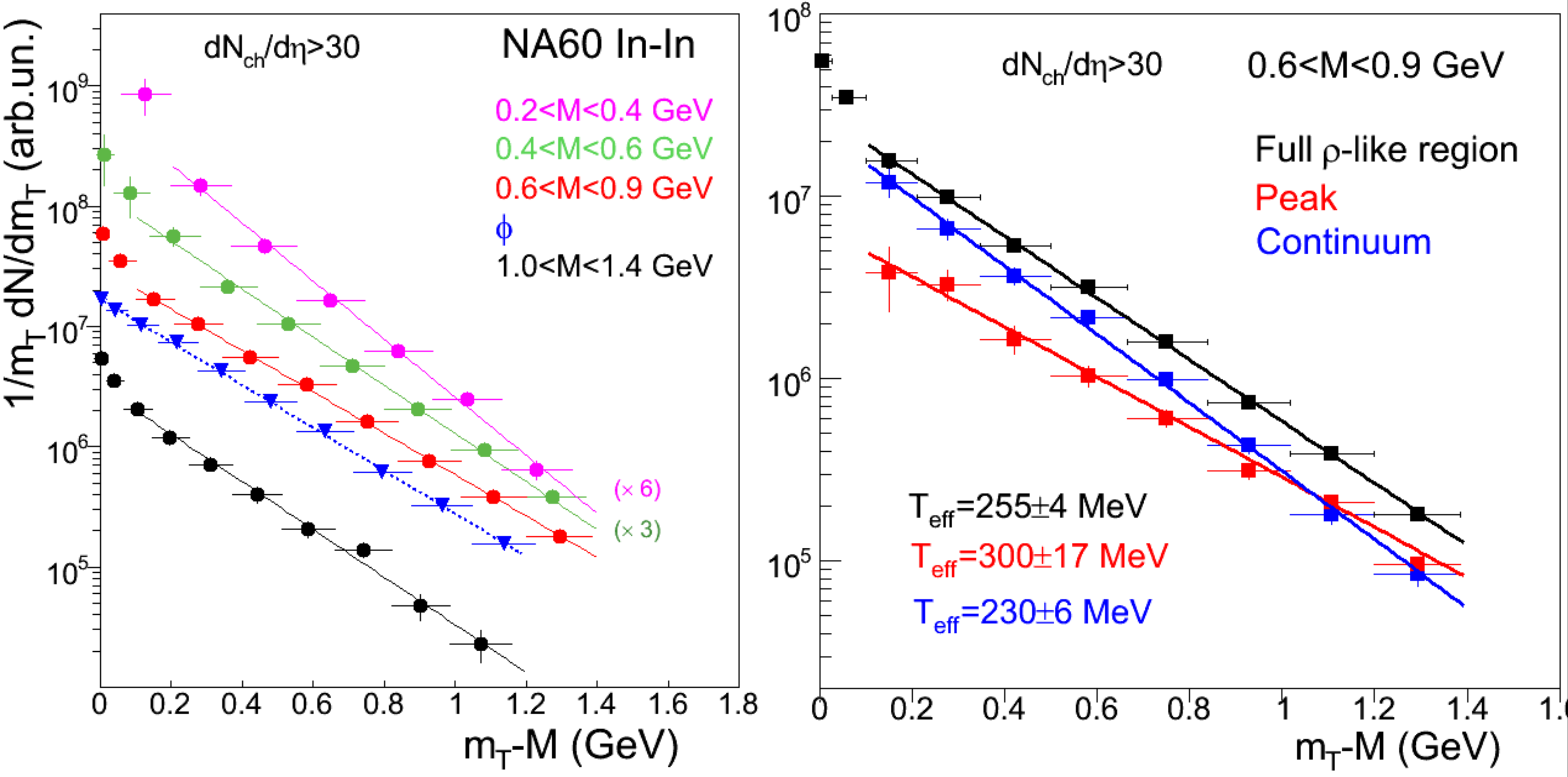
NA60 Analysis of m_T spectra

PRL 96 (2006) 162302

- Decomposition of low mass region:
  - contributions of mesons (η, ω, ϕ)
  - continuum plus ρ meson
  - extraction of vacuum ρ
- Hadron m_T spectra for:
  - η, ω, ϕ
  - vacuum ρ
- Dilepton m_T spectra for:
  - low mass excess
  - intermediate mass excess



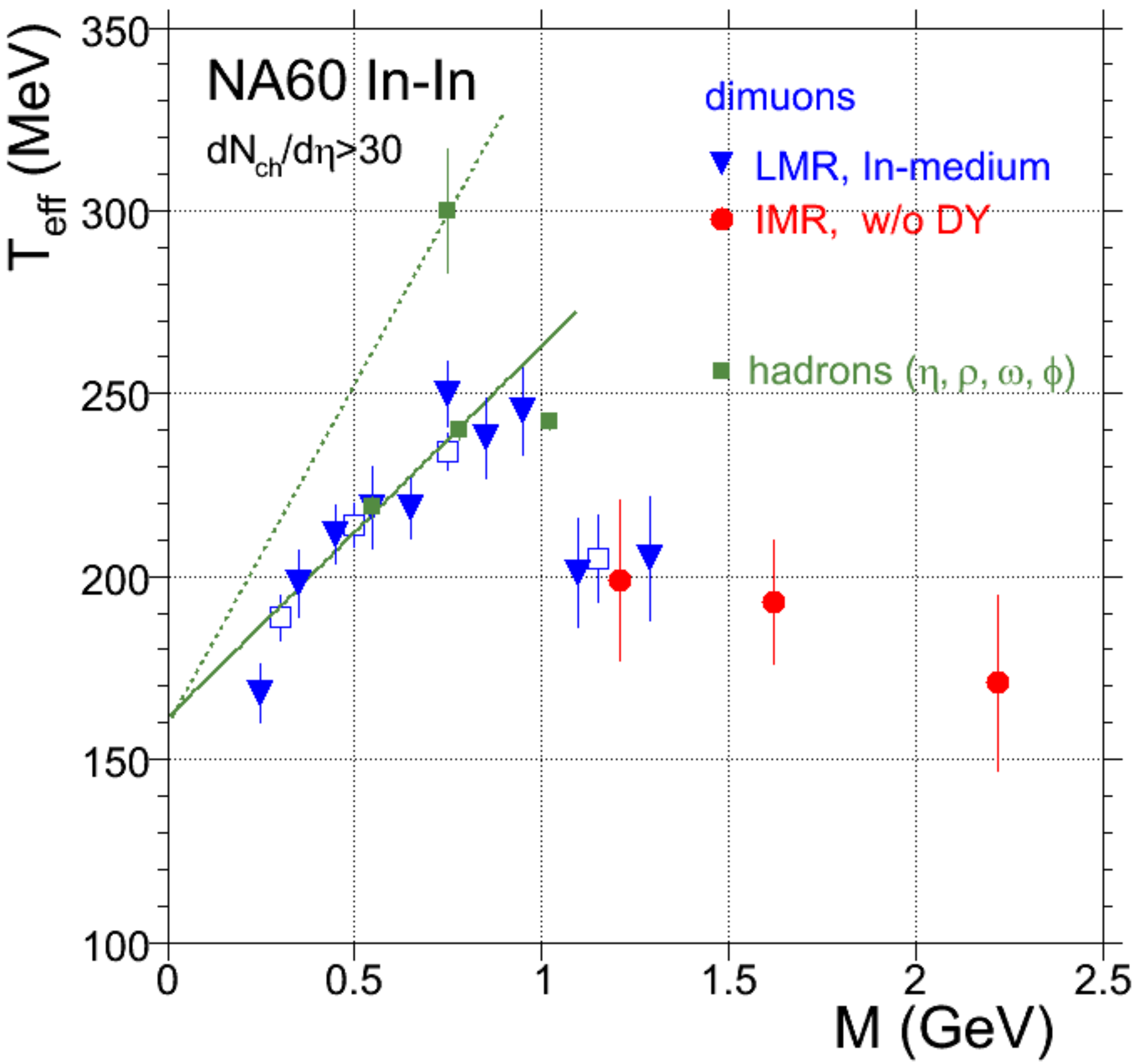
Examples of m_T Distributions



Dilepton T_{eff} Summary

- Hadrons (η, ω, ρ, ϕ)
  - T_{eff} depends on mass
  - T_{eff} smaller for ϕ decouples early
  - T_{eff} large for ρ decouples late
- Low mass excess
  - Clear flow effect visible
  - Follows trend set by hadrons
  - Possible late emission
- Intermediate mass excess
  - No mass dependence
  - Indication for early emission

EPJ C 61 (2009) 711



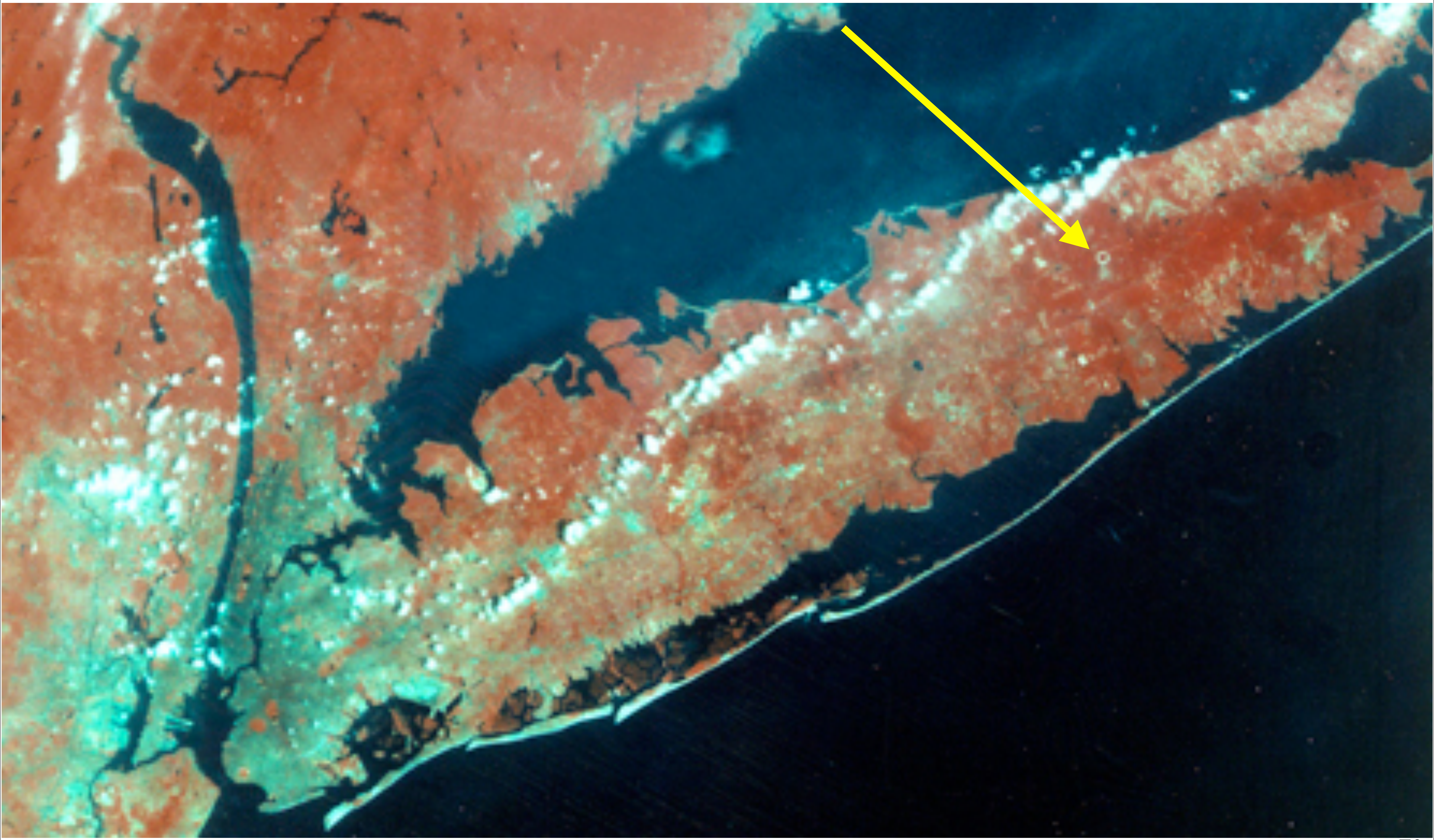
What did we get from NA60

- High statistics & high precision dimuon spectra
- Decomposition of mass spectra into “sources”
- Gives access to in-medium ρ spectral function
- Data consistent with broadening of the ρ
- Data do not require mass shift of the ρ
- Large prompt component at intermediate masses
- Dimuon m_T spectra promise to separate time scales
  - Low mass dimuons shows clear flow contribution indicating late emission
  - Intermediate mass dimuons show no flow contribution hinting toward early emission

RHIC

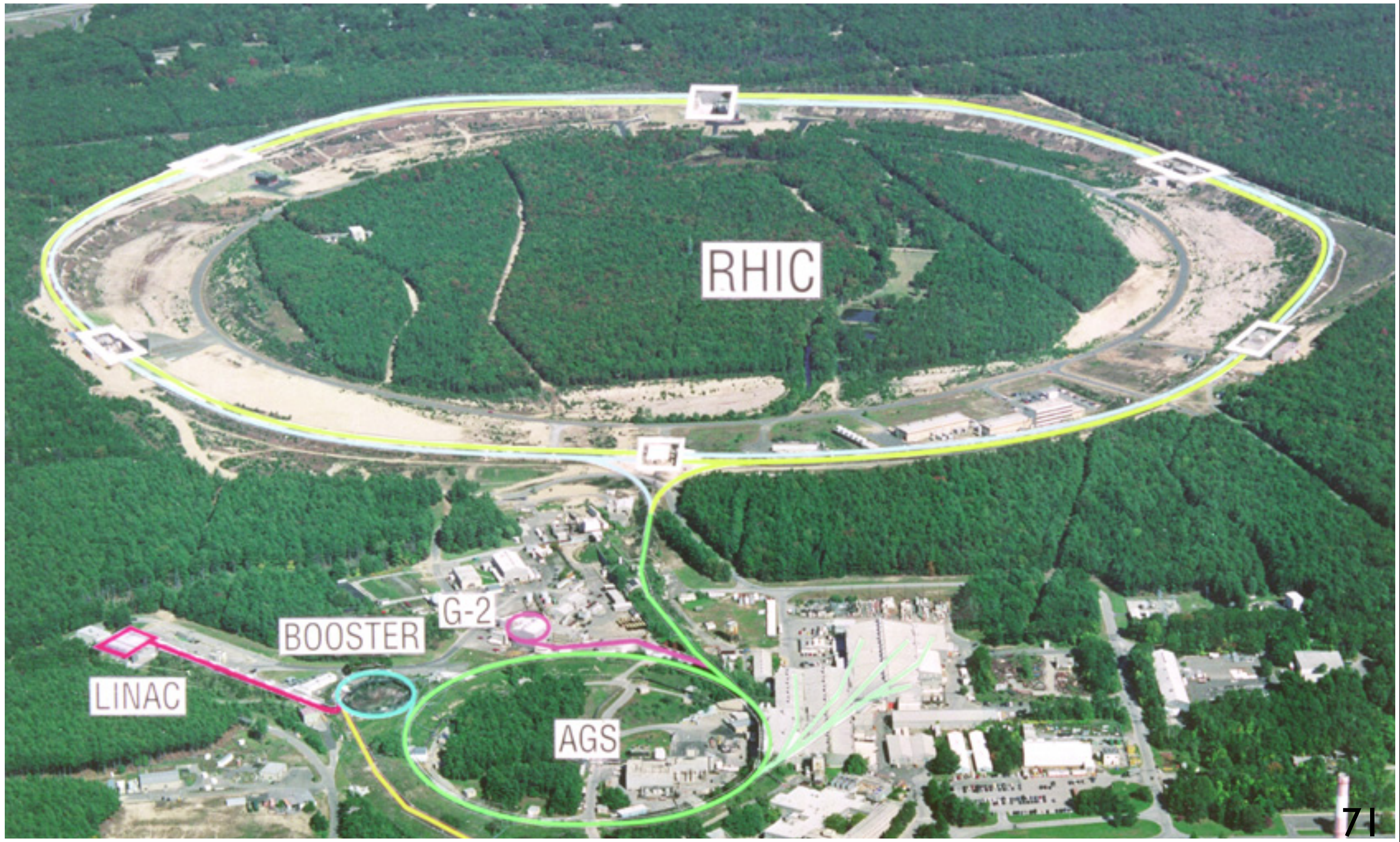
RHIC at BNL

Relativistic Heavy Ion Collider at Brookhaven National Lab



Experiments at RHIC

- What is so special about RHIC?
  - It is a collider
    - No thick targets
    - Detector systematics do not depend on E_{CM}
  - p+p: $\sqrt{s} \leq 500$ GeV (polarized beams)
  - A+A: $\sqrt{s_{NN}} \leq 200$ GeV (per nucleon–nucleon pair)
- Experiments with specific focus
  - BRAHMS (until Run-6, 2006)
  - PHOBOS (until Run-5, 2005)
- Multi purpose experiments
  - PHENIX
  - STAR



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  - PHENIX
  - STAR

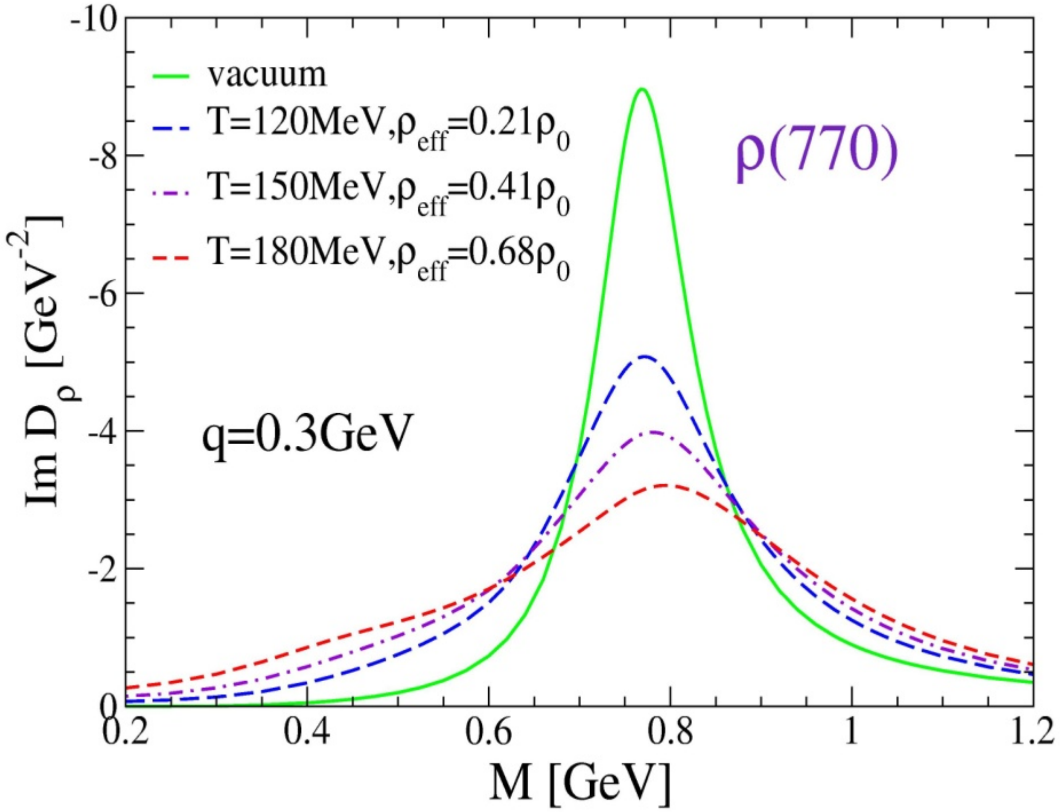
From SPS to RHIC

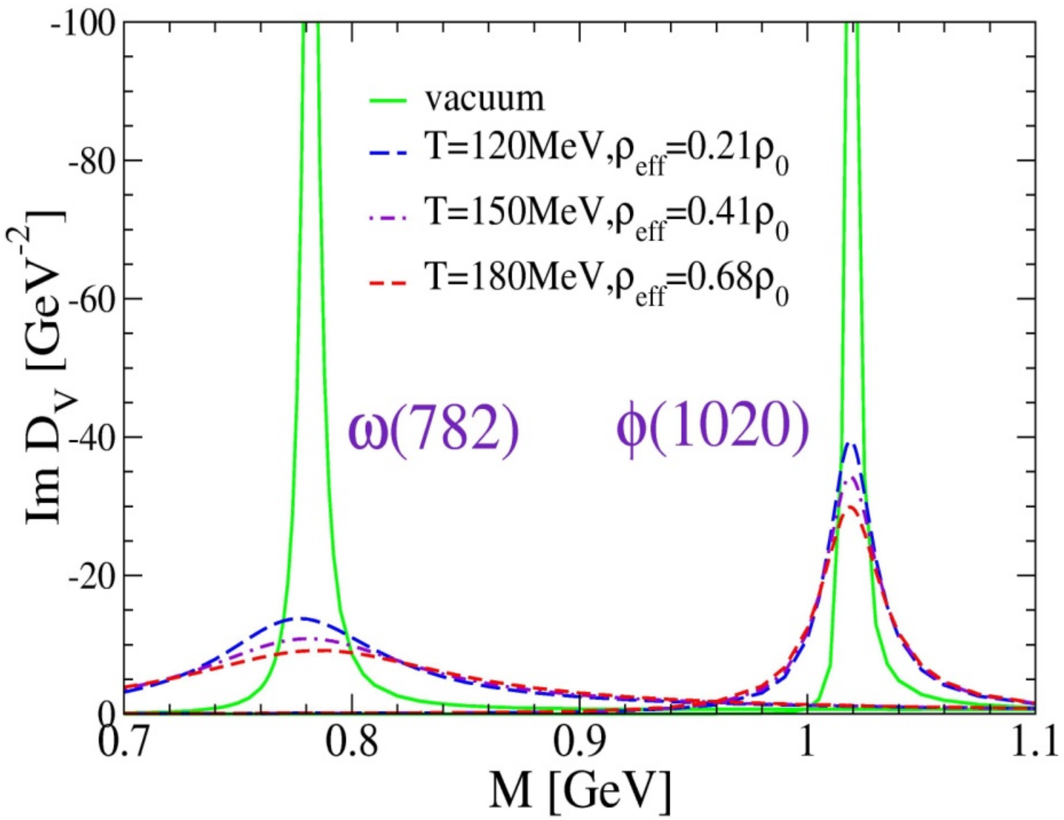
- 2 scenarios @ SPS profit from high baryon density
  - dropping ρ mass
  - broadening of ρ
- What to expect at RHIC?
  - increase of centre-of-mass per nucleon-nucleon pair from 17 to 200 GeV

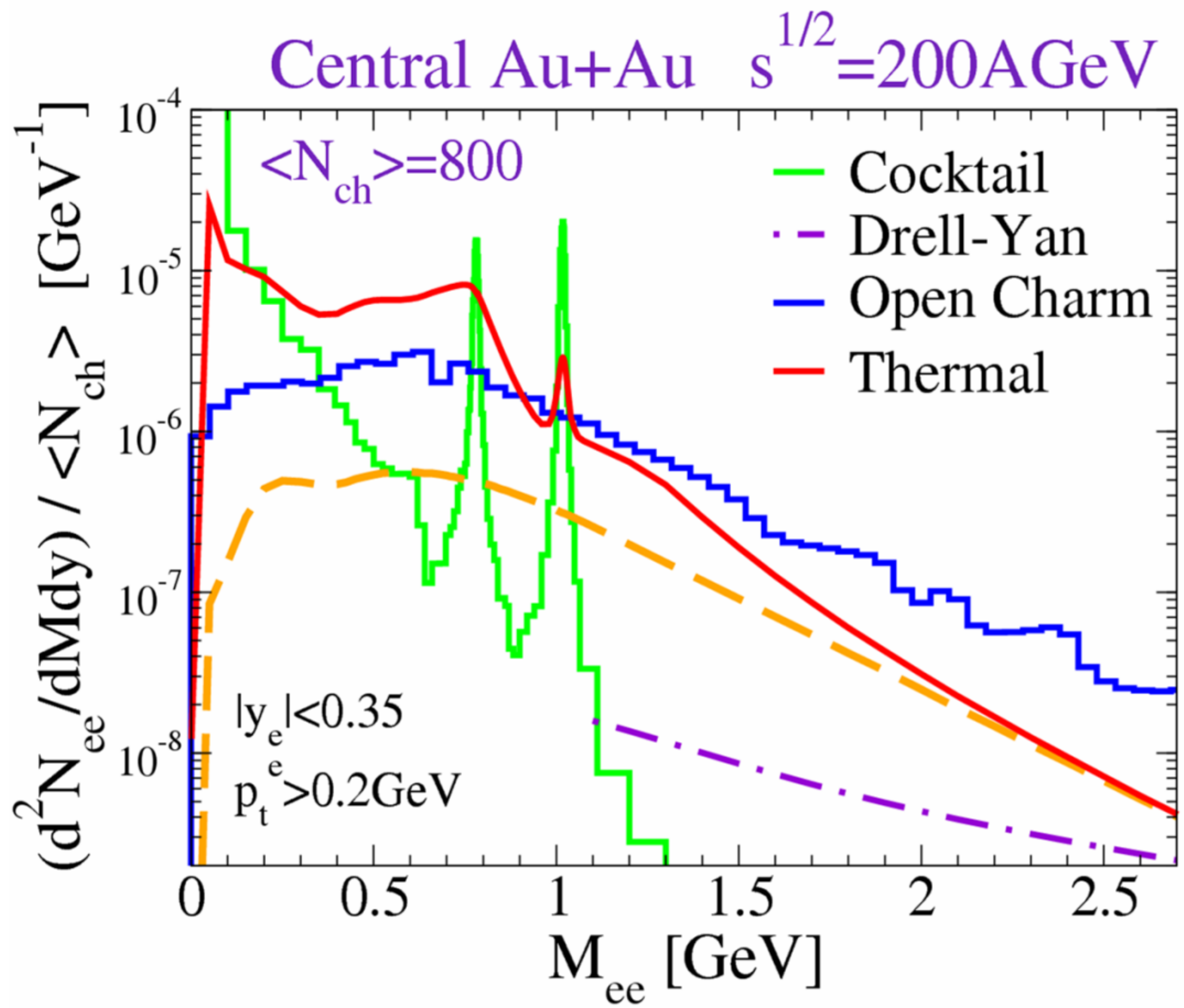
	SPS (Pb+Pb)	RHIC (Au+Au)
$dN(\bar{p})/dy$	6.2	20.1
produced baryons (p, $\bar{p}$, n, $\bar{n}$)	24.8	80.4
$p - \bar{p}$	33.5	8.6
particpating nucleons $(p - \bar{p})A/Z$	85	21.4
total baryon number	110	102

- Baryon density: almost the same at SPS & RHIC (although the NET baryon density is not!)

Expectations at RHIC





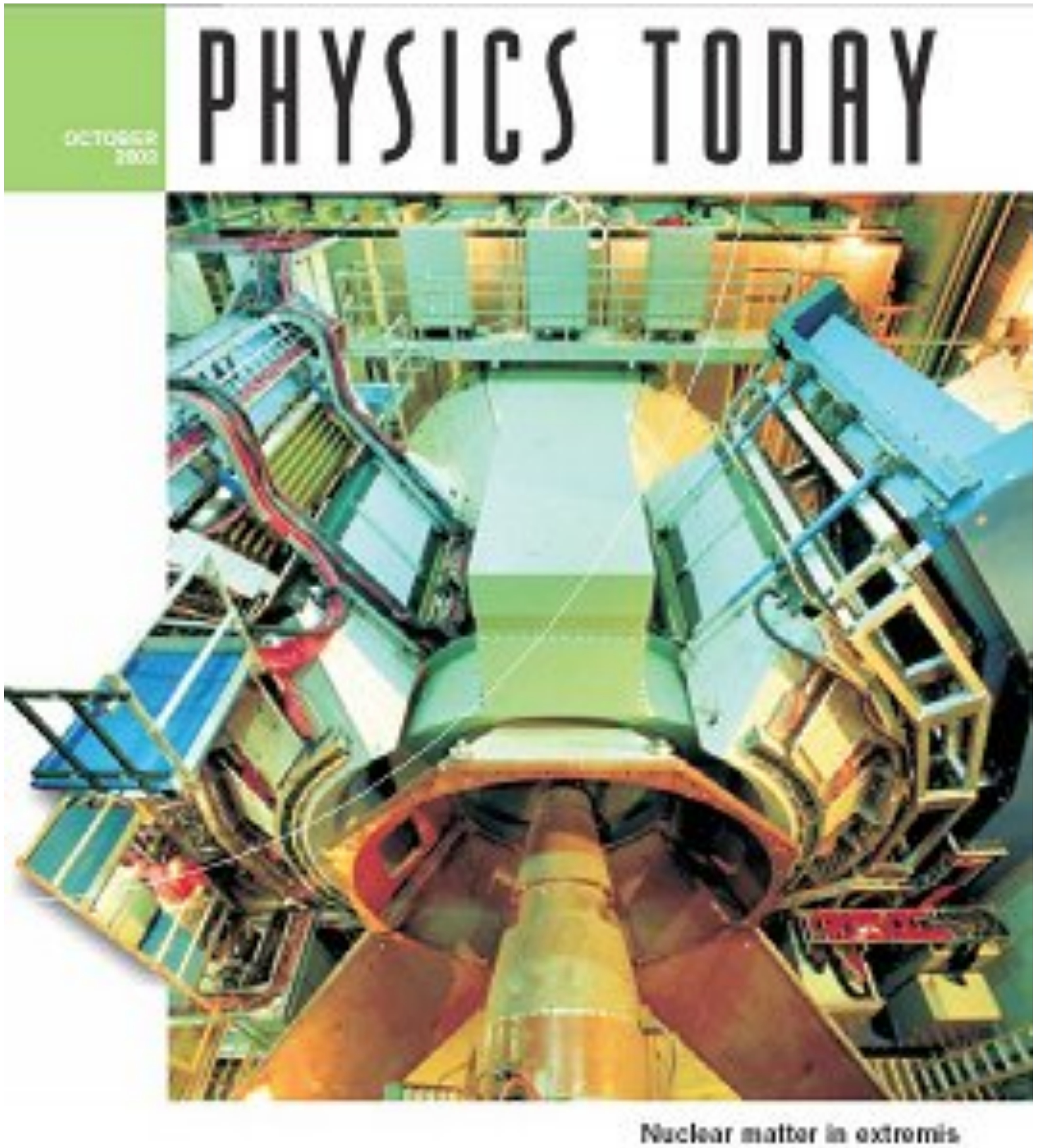


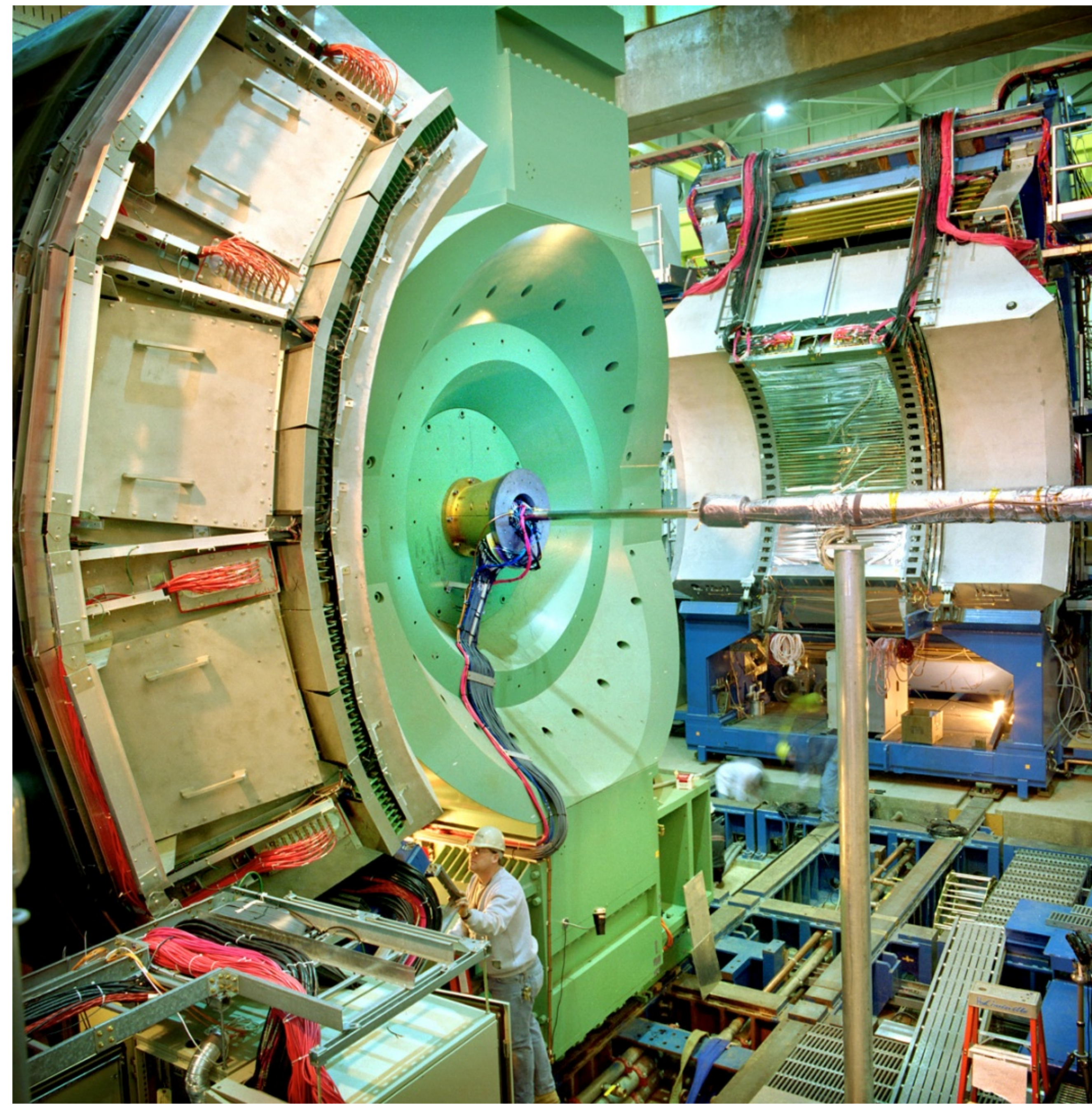
- In-medium modifications of vector mesons persists
- Open charm contribution becomes significant

The founding fathers' view

- Before 1991:
  - proposals for various experiments at RHIC
    - STAR, TALES, SPARC, OASIS, DIMUON …
    - except for STAR everything else is burned down
  - from the ashes rises PHENIX
    - Pioneering High Energy Nuclear Interaction eXperiment
- 1991: PHENIX "conceptual design report"
  - philosophy
    - measure simultaneously as many observables relevant for QCD phase transitions as you can imagine
    - all but one: low-mass dielectrons
  - why no dielectrons?
    - included in first TALES proposal
    - considered to be "too difficult" for PHENIX
- A lot of work can make impossible things happen

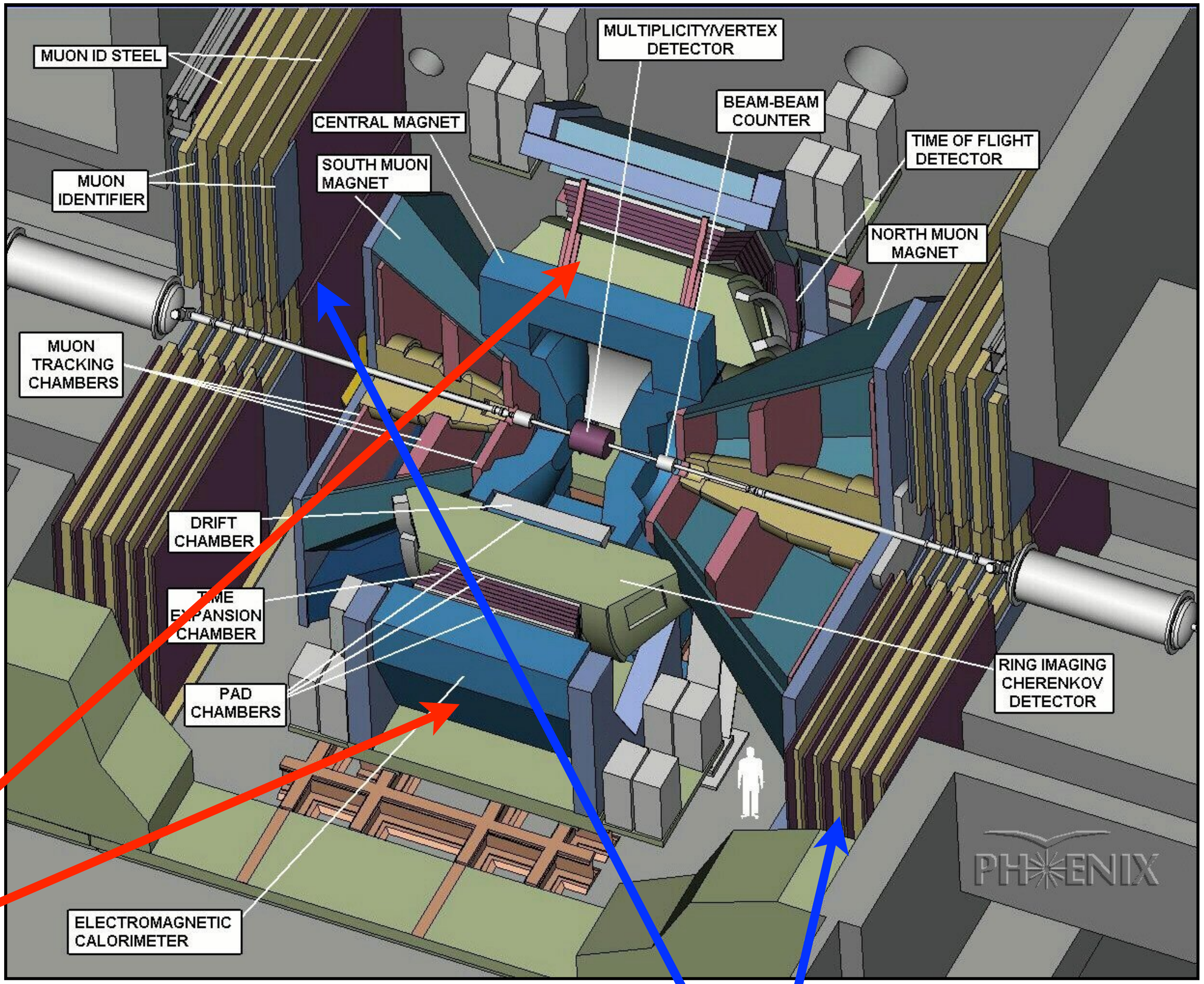
The PHENIX detector at RHIC





The PHENIX detector at RHIC

- 3 detectors for global event characterisation
- Central spectrometers
  - measurement in range:
    $|\eta| \leq 0.35$
    $p \geq 0.2$ GeV/c
- Forward spectrometers
  - muon measurement in range:
    $1.2 < |\eta| < 2.4$
    $p \geq 2$ GeV/c

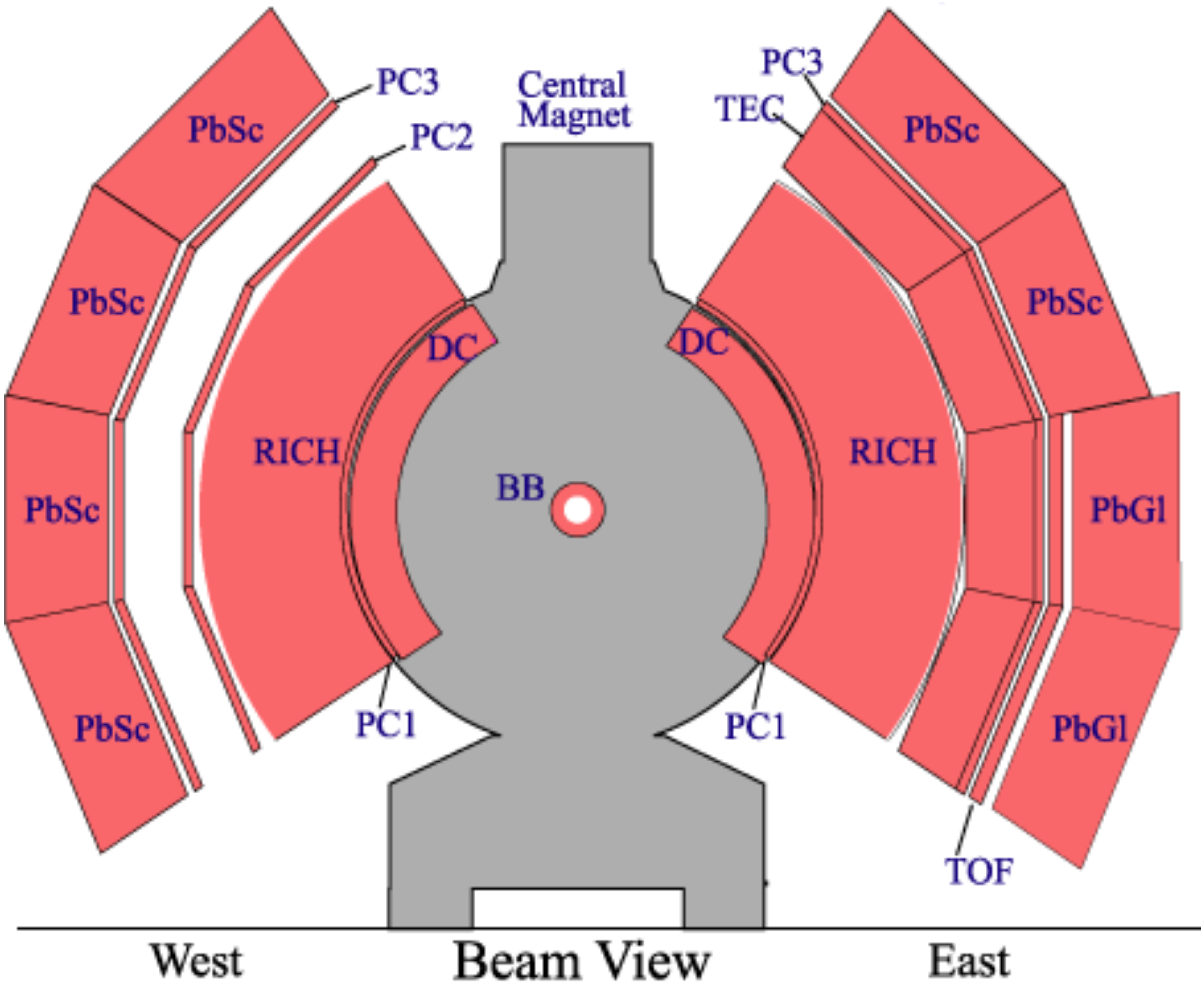


two central electron/photon/hadron spectrometers

two forward muon spectrometers

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

PHENIX Particle Tracking and ID



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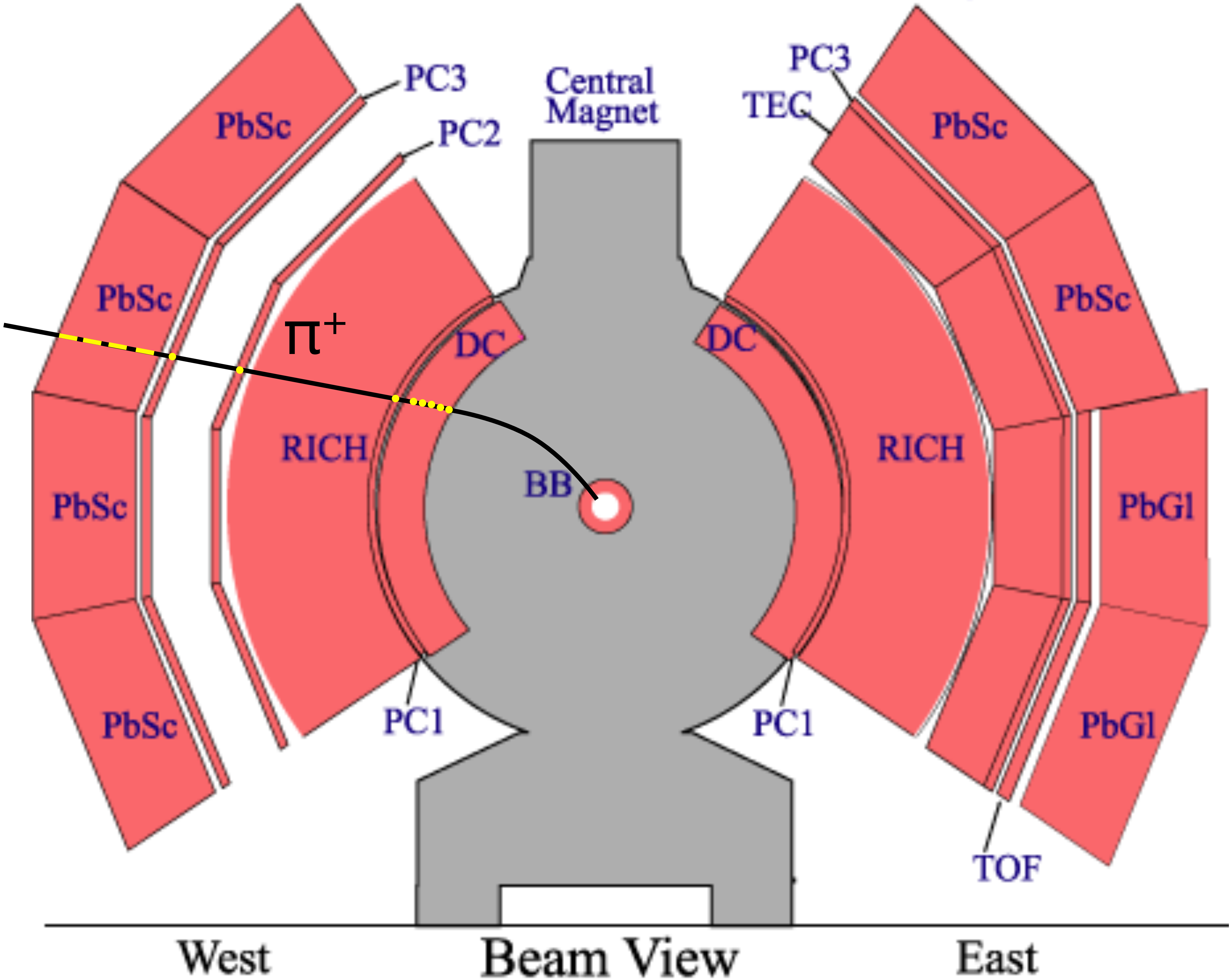

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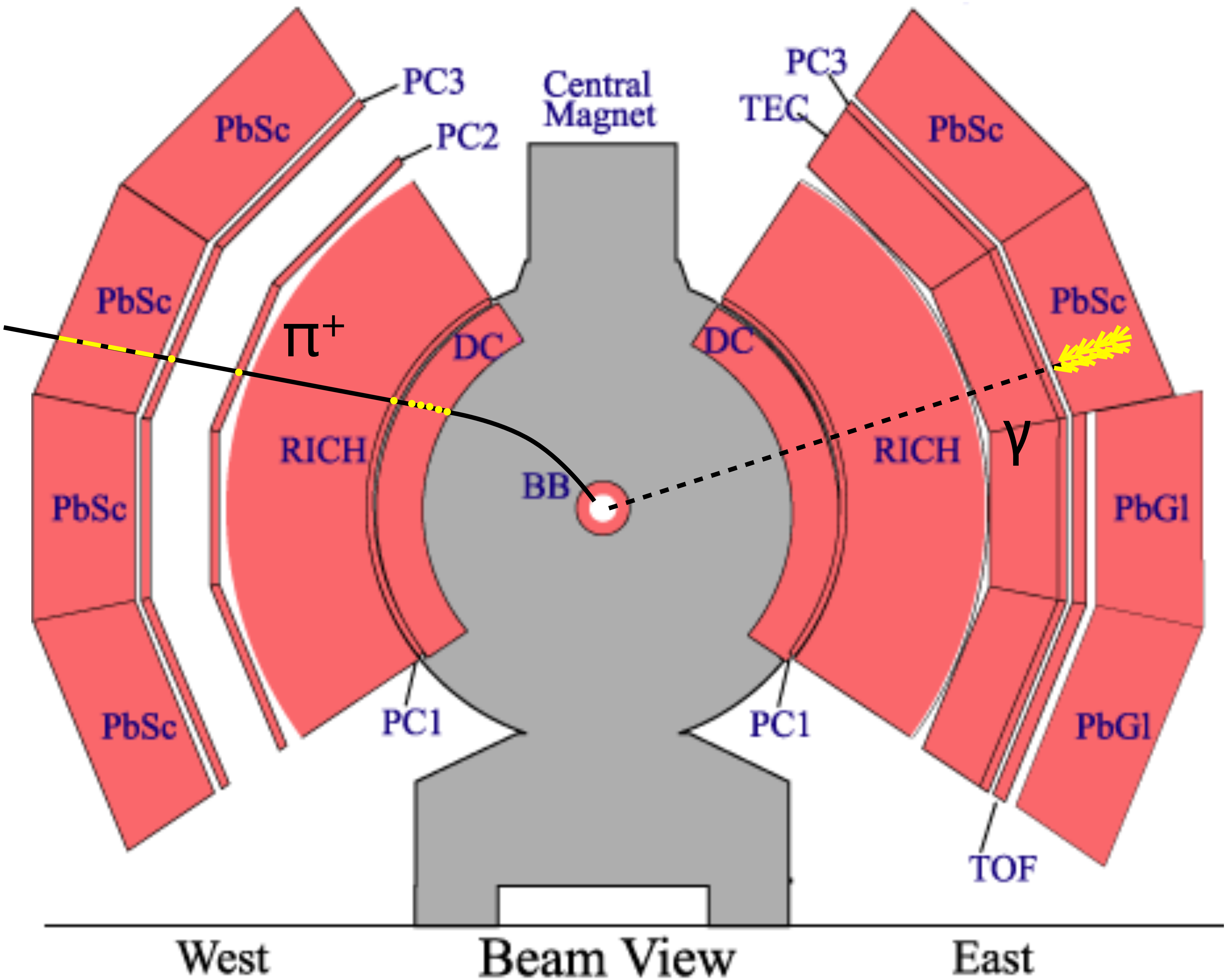

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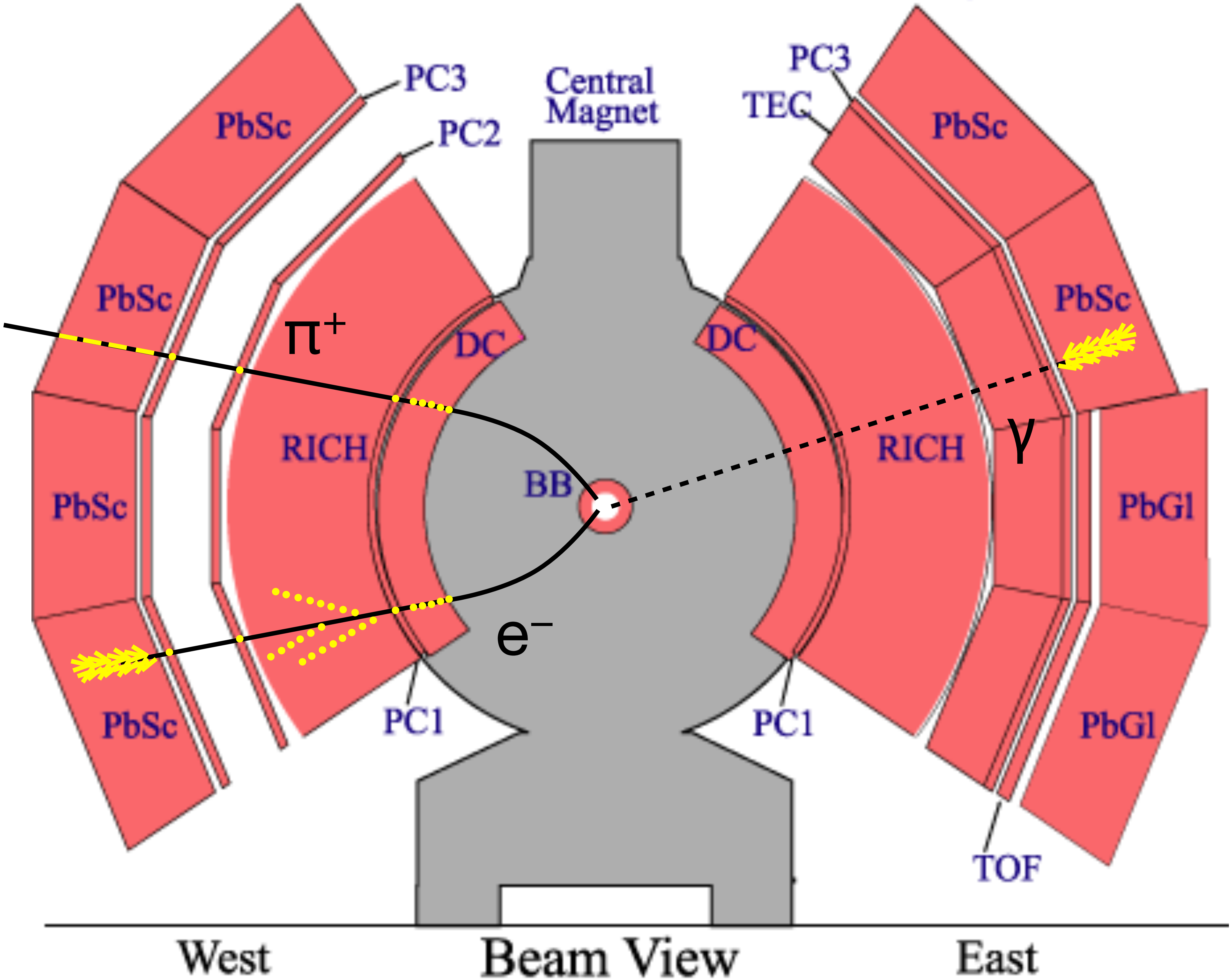

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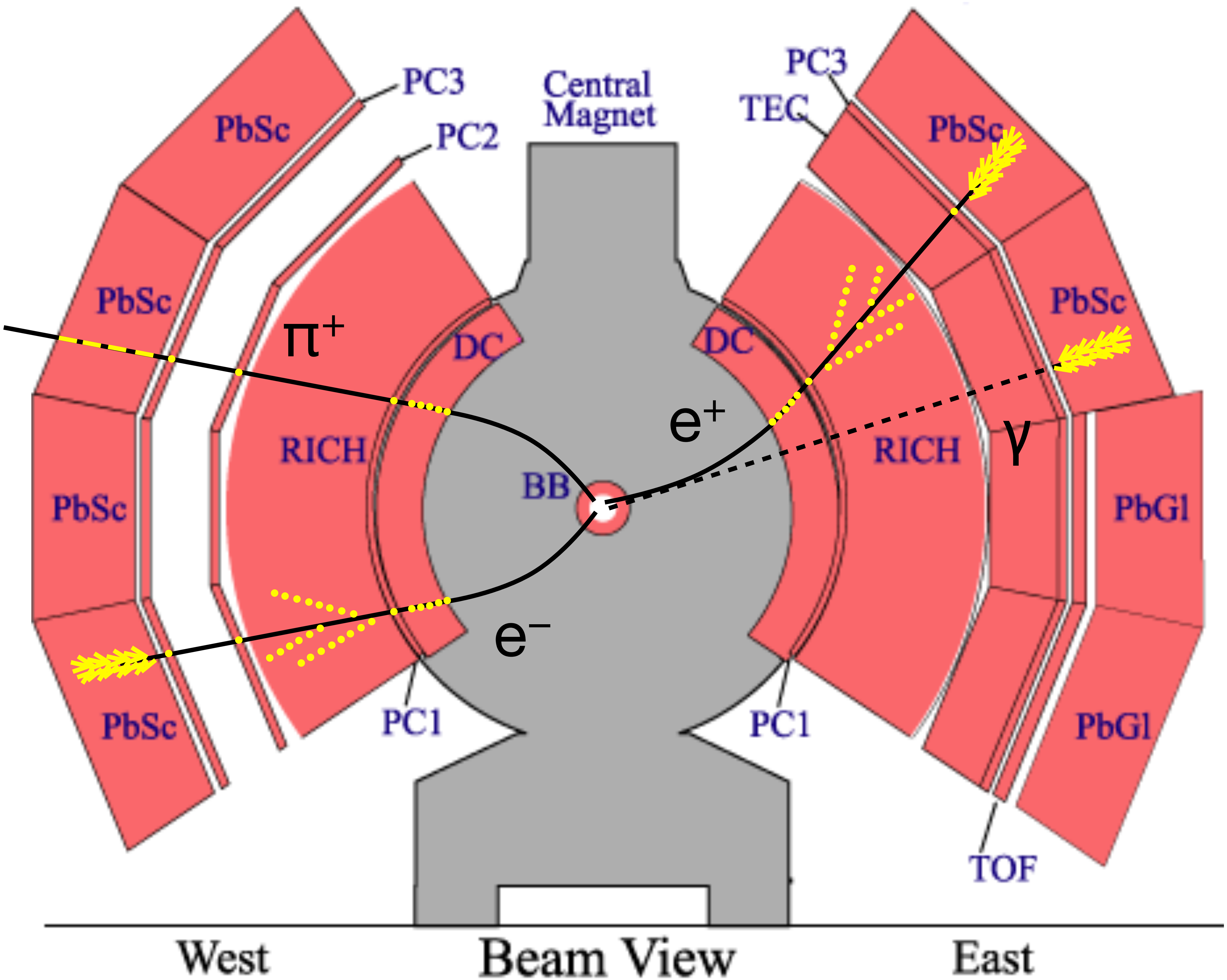
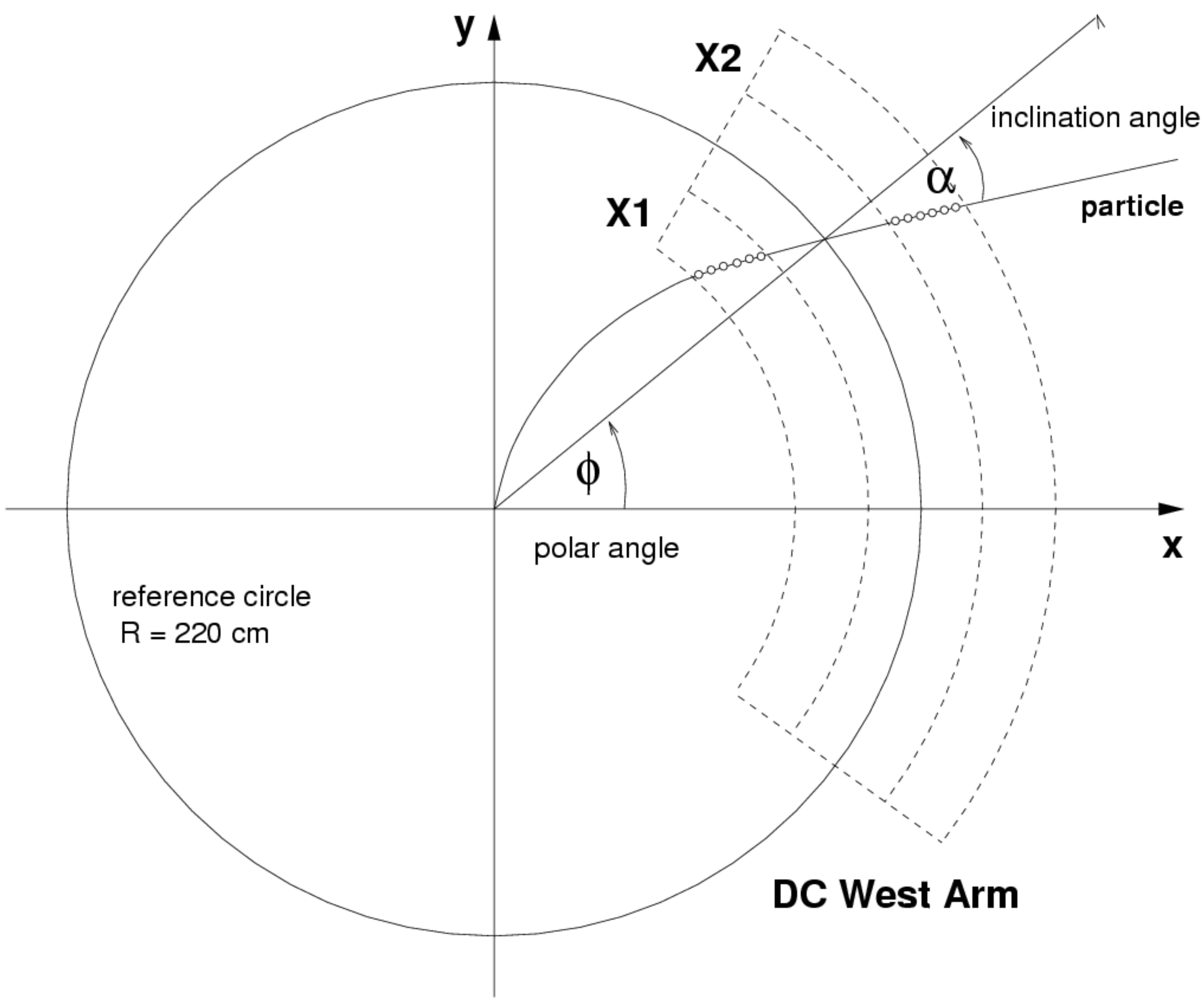


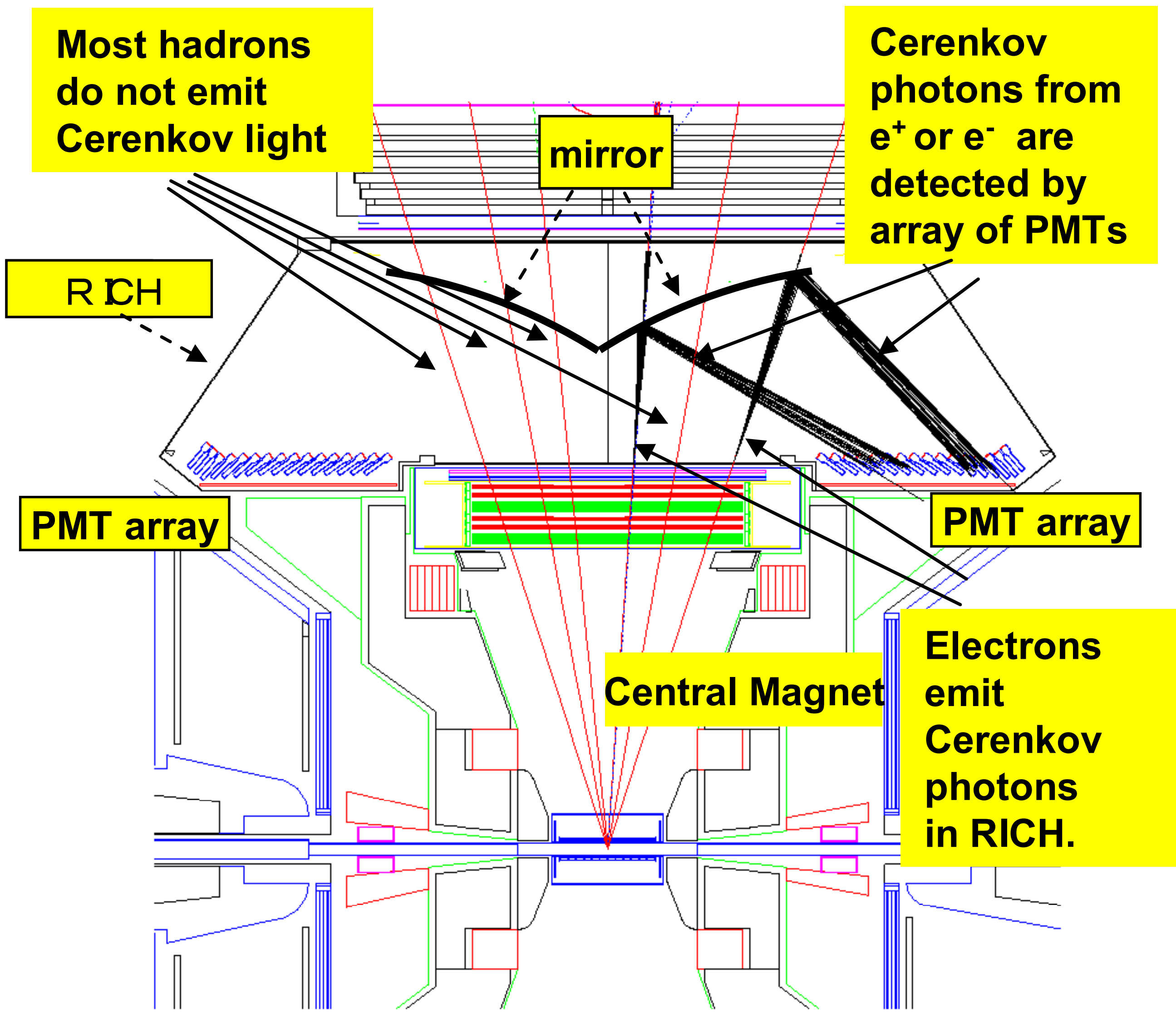
Momentum Determination

- Simple relation between bending angle and momentum:
  $\alpha = K/p_T$ (with K ~ 0.206 rad GeV/c, depends on magnetic field)



Electron Identification I

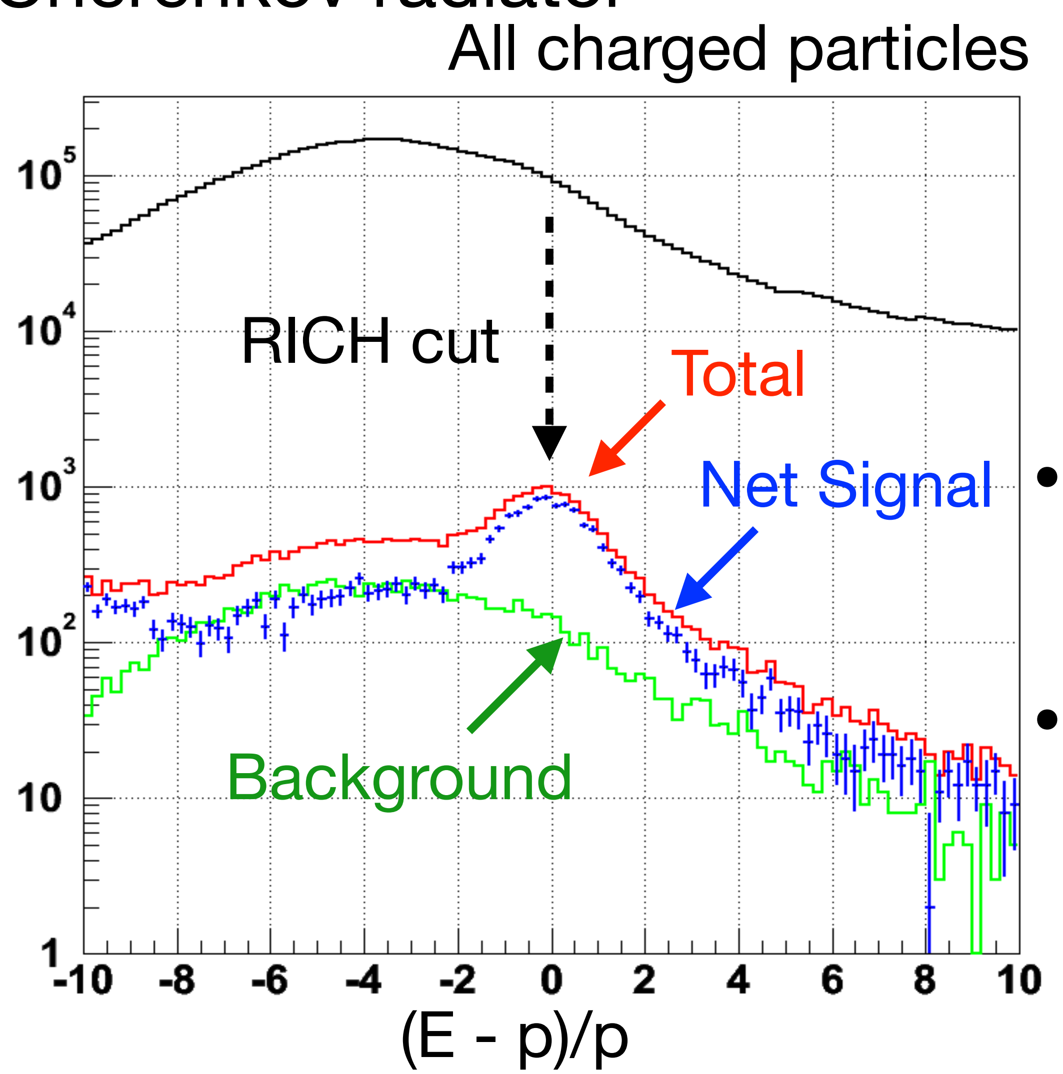
- Charged particle tracking
  - DC, PC1, PC2, PC3 and TEC
  - Target: mass resolution of 1%
- PHENIX optimized for Electron ID
  - Cherenkov light RICH +
  - shower EMCAL



- Emission and measurement of Cherenkov light in the Ring Imaging Cherenkov detector measure of minimum velocity
- How can pions ever be misidentified below 4.9 GeV/c?
  - Radiation of Cherenkov light (≥ 4.9 GeV/c)
  - Production of delta electrons
  - Random coincidence (high multiplicity)
  - spherical mirror
    - parallel tracks produce rings at SAME location

Electron Identification II

- Production of em. shower in the Electro-Magnetic Calorimeter
  - measure of energy E
- PbSc: sampling calorimeter, layers of lead and scintillator
- PbGl: homogeneous lead-glass volume, Cherenkov radiator
- $e^{\pm}$: $E \approx p$
- $h^{\pm}$: $E < p$



- After RICH cuts: clear $e^{\pm}$ signal
- Cut on E/p cleans $e^{\pm}$ sample!
- Main background source:
  - random combination of hadron track with uncorrelated RICH ring
  - "Statistical" subtraction technique:
    - Flip-and-slide of RICH
    - Swapped background agrees in shape with E/p distribution of identified hadrons
    - Does not work for pair analysis
- Other background:
  - photon conversions (real electrons)
- Background increases with detector occupancy (can reach ~30% in central Au+Au collisions)

Background

Type I: identified on a pair-by-pair basis

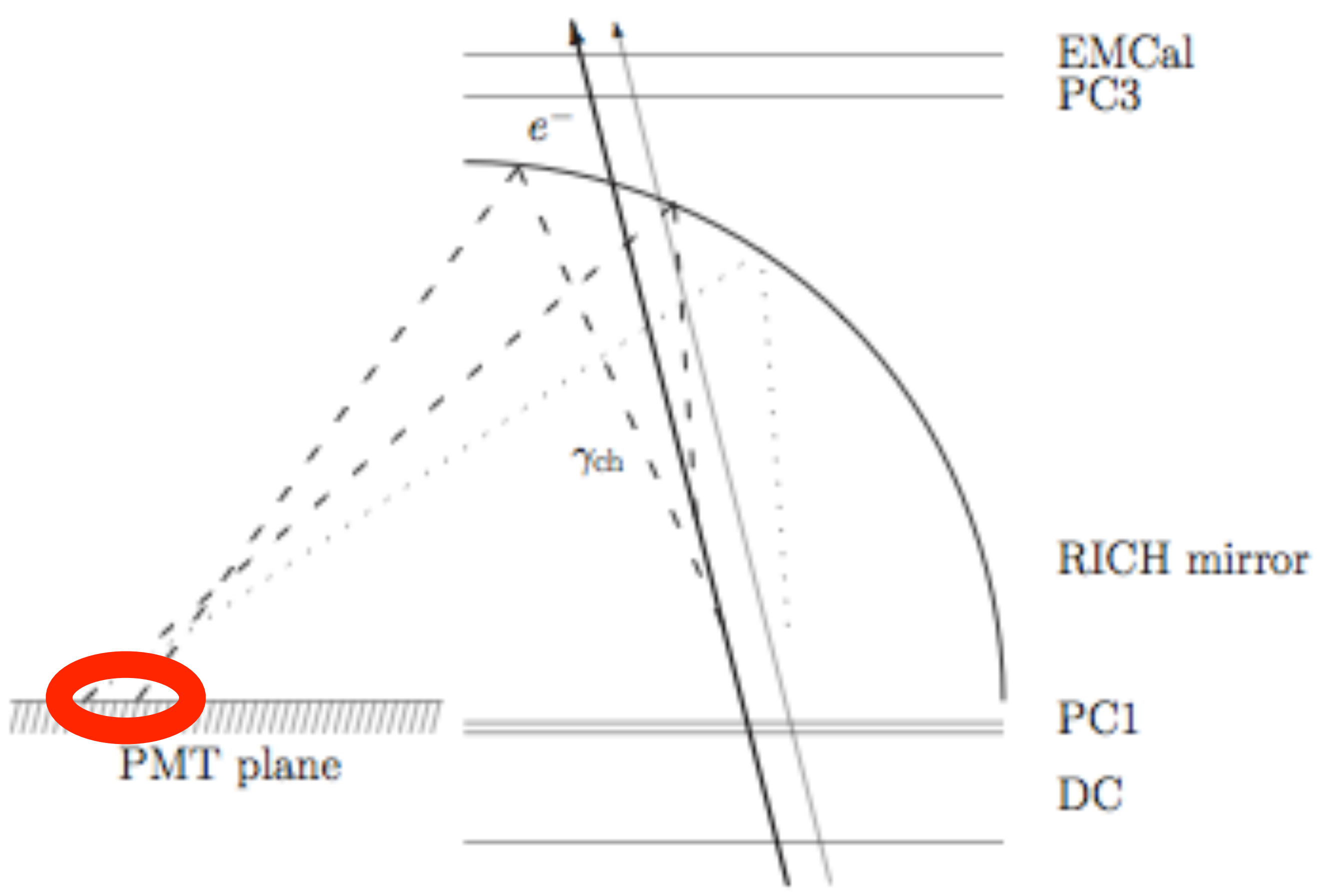
- Overlapping hits in the detectors (mostly RICH)
- Photon conversions

Type II: cannot be identified on pair-by-pair basis removed statistically

- Combinatorial (B_{comb}):
  - all combinations where the origin of the two electrons is totally uncorrelated
- Correlated (B_{corr}):
  - Cross pairs: Two e^+e^- pairs in the final state of a meson
  - Jet pairs: Two hadrons within the same jet or in back-to-back jets, decay into e^+e^- pairs

Overlapping Pairs

- If $h^{\pm}$ points to the same ring as $e^{\pm}$
  - associated to the same ring
  - considered as $e^{\pm}$
- Happens for typical values of opening angle (different for like and unlike sign), which folded with the average momentum of the electron corresponds to a particular invariant mass (different for like and unlike sign)
  - cut: requested minimum distance between the rings (~1 ring diameter)
- Cut applied as event cut:
  - Real events: discarded and never reused
  - Mixed events: regenerated to avoid topology dependence



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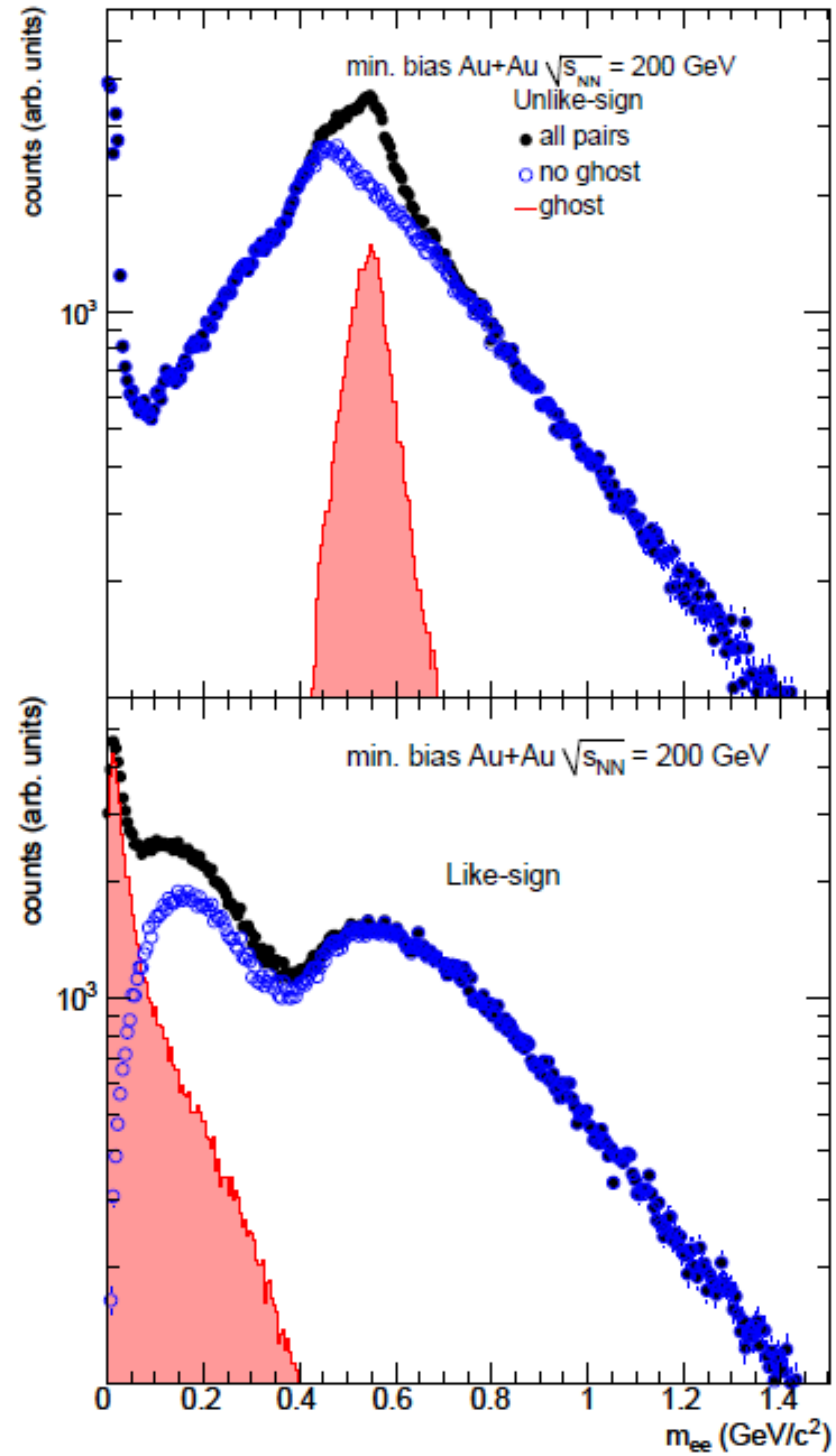
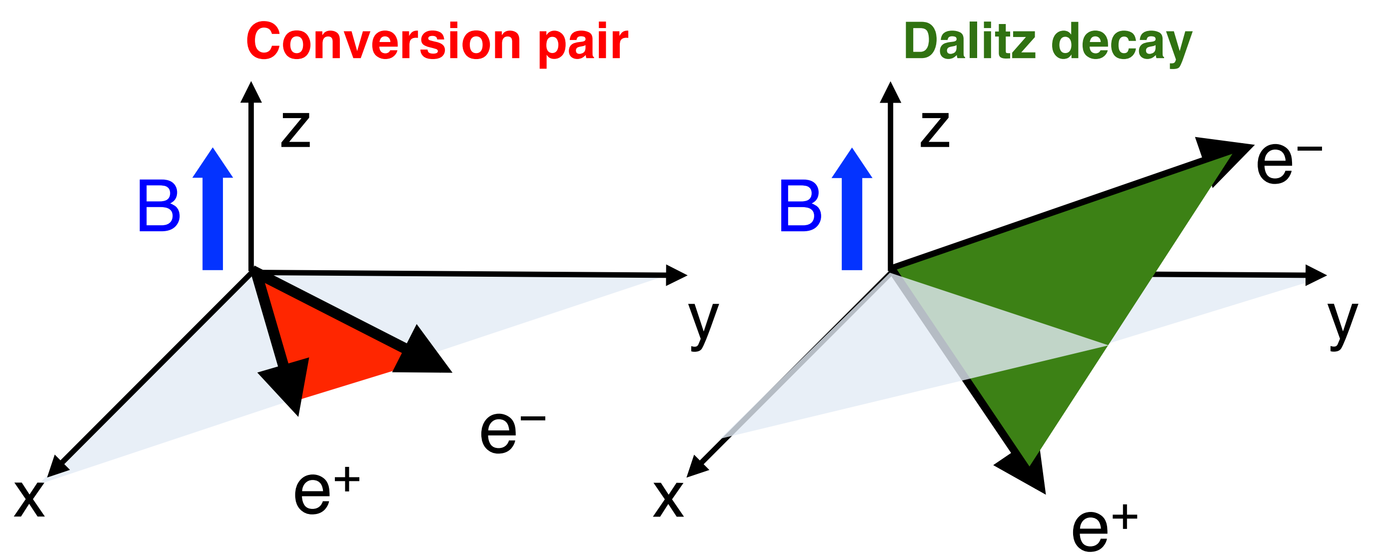
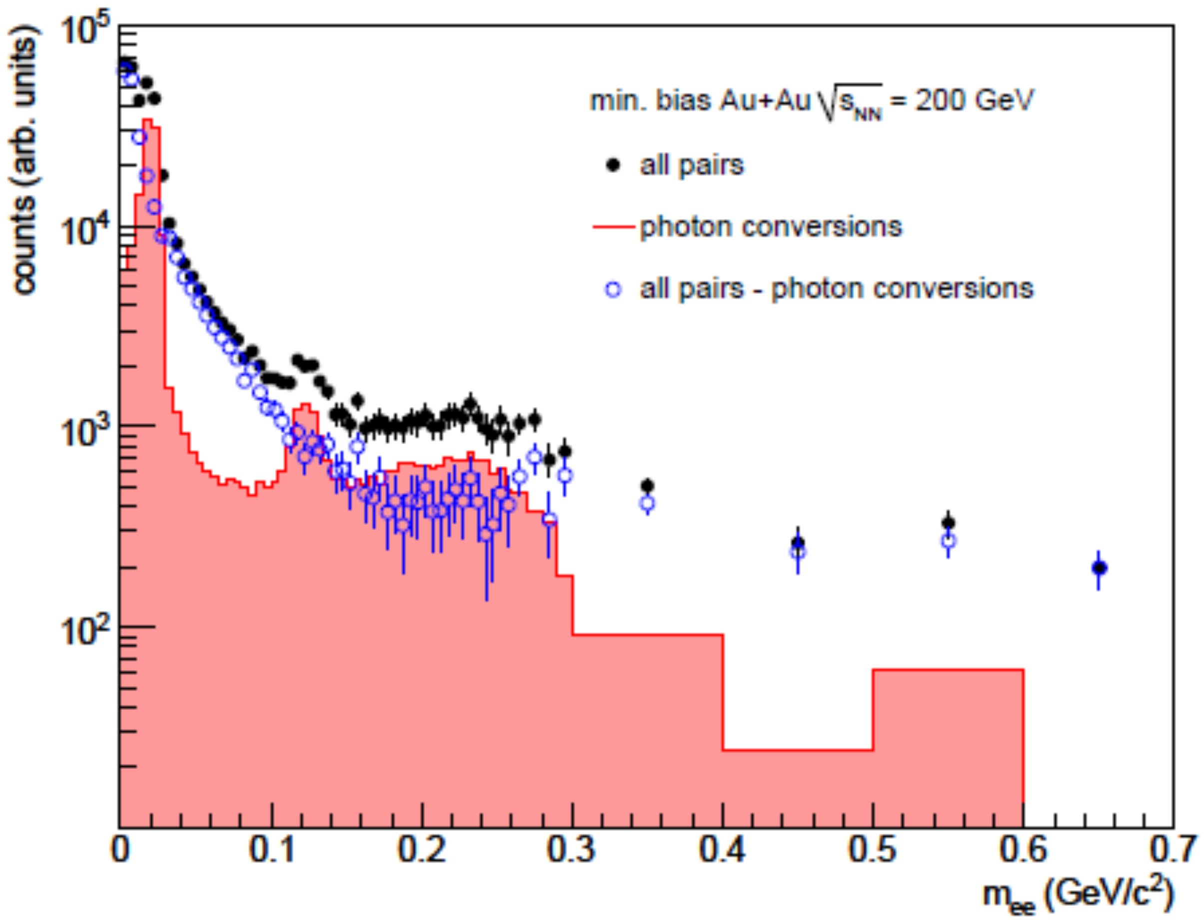
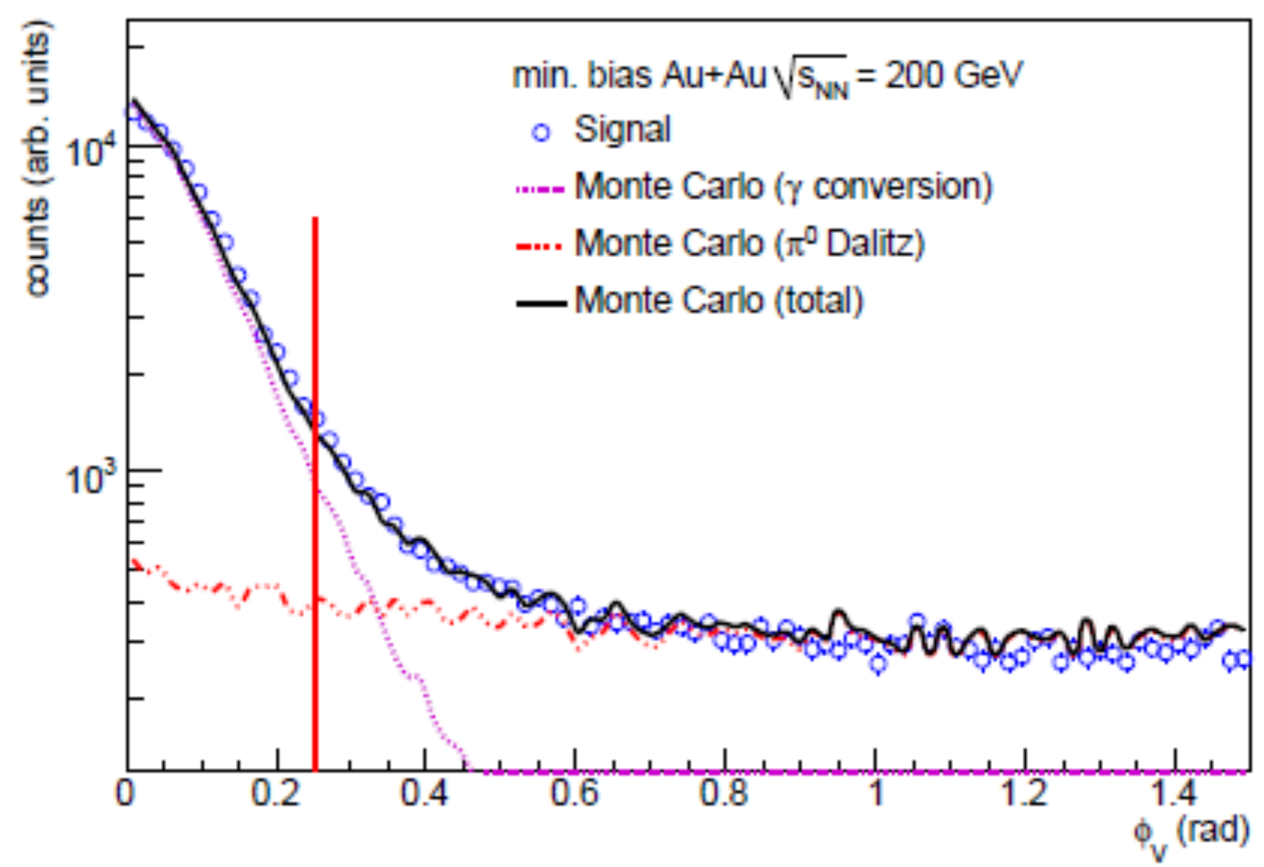


Photon Conversion Rejection

- Artefact of PHENIX tracking
  - assume that all tracks originate from the vertex
  - off vertex tracks → wrong momentum vector
  - ➡ Conversions are reconstructed with $m \neq 0$ ($m \sim r$)
- Conversions "open" in a plane perpendicular to the magnetic field





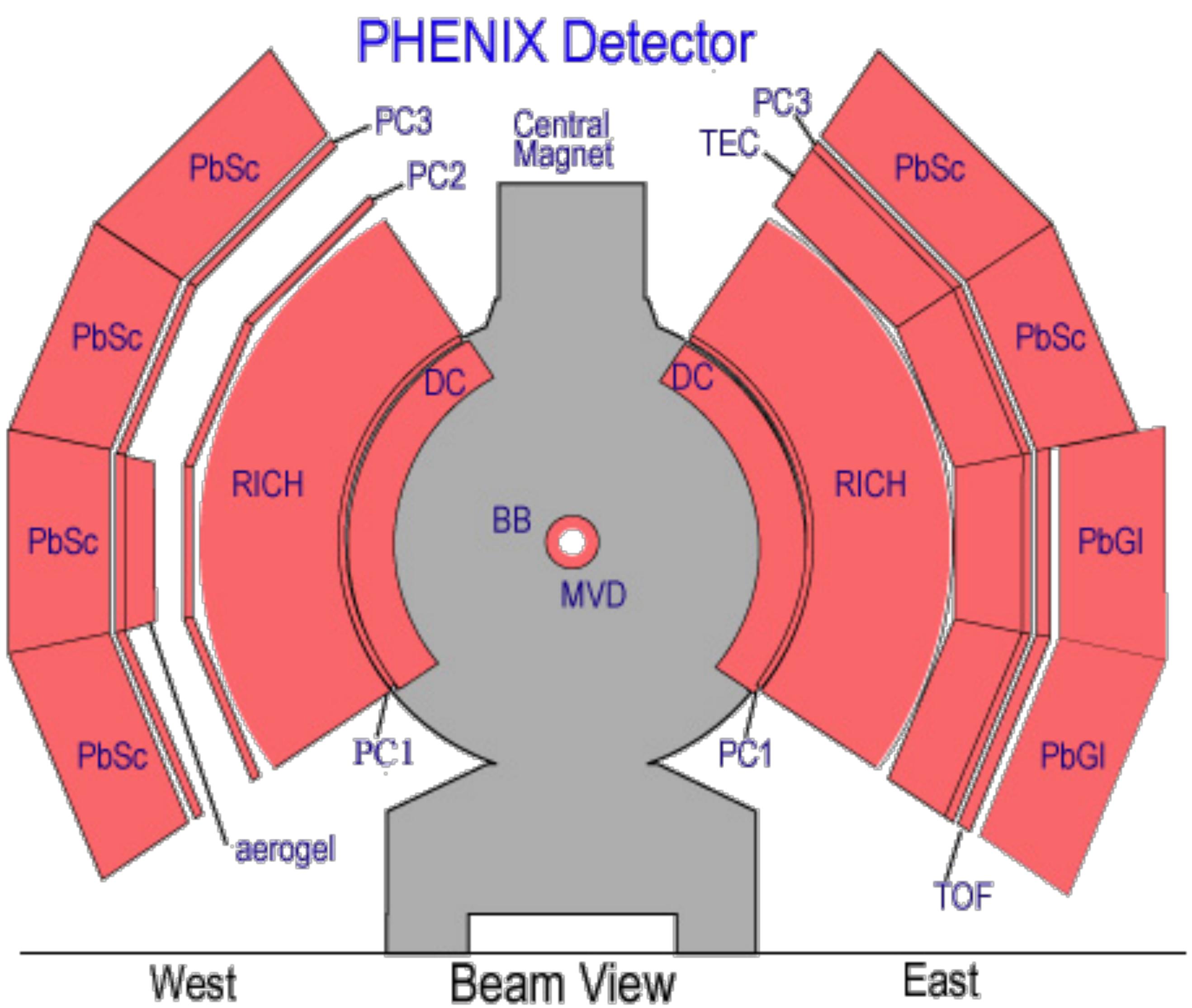


Low-mass e^+e^- pairs: the Problem

- Average number of electrons/event in PHENIX:
  - $N_e = (dN/d\eta)_{\pi^0} \times$ (BR+CONV) $\times$ acceptance $\times$ $f(p_T > 0.2\text{GeV})$
    350 (0.012+0.02) 0.5×0.7 0.32 = 1.3
- Combinatorial background pairs/event
  - $B = N_e^2 / 2! \ \exp(-N_e) = 0.2$ (assume Poisson distribution)
- Expected signal pairs/event ($m > 0.2$ GeV, $p_T > 0.2$ GeV)
  - $S = 4.2\times10^{-4}$

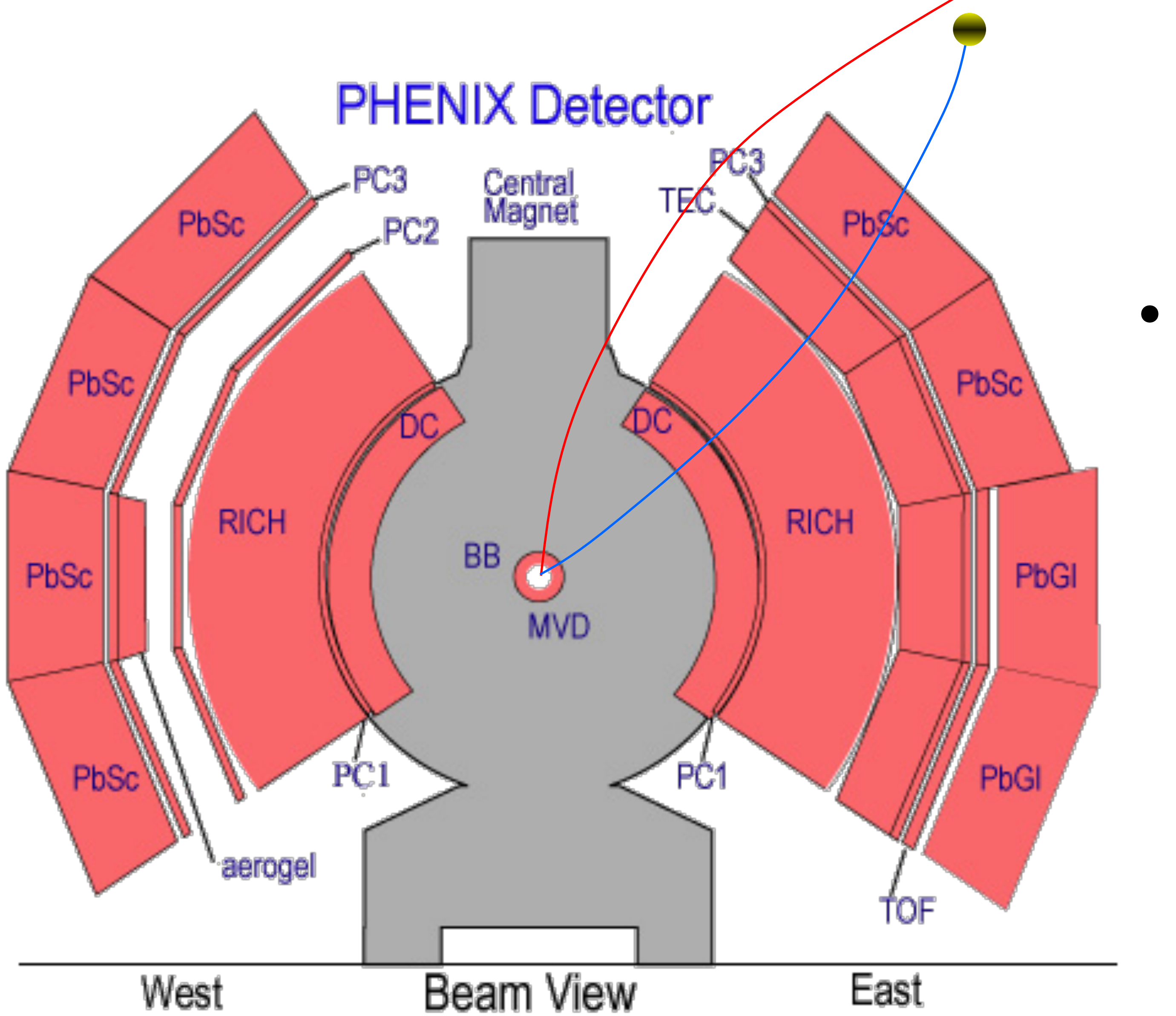
➡ Signal/Background
  - as small as 1/ few hundred
  - depends on mass
- What can we do to reduce the combinatorial background?
- Where does it come from?

Conversion/Dalitz rejection?



- Typically only one “leg” of the pair is in the acceptance
    - Acceptance holes
    - “Soft” tracks curl up in the magnetic field
- Only (!) solution:
    - Catch electrons before they are lost
    - Need new detector and modification of magnetic field

Conversion/Dalitz rejection?



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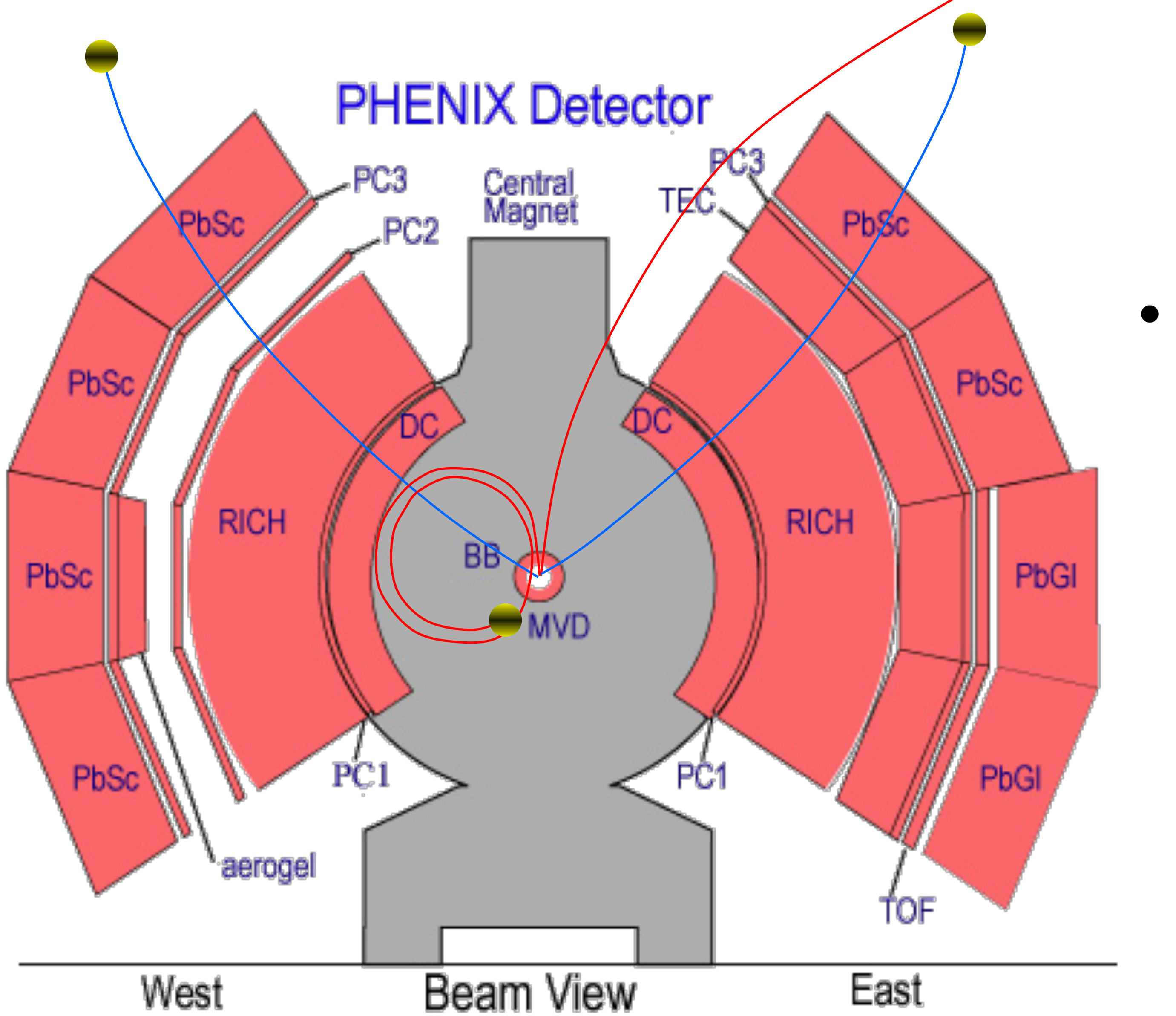

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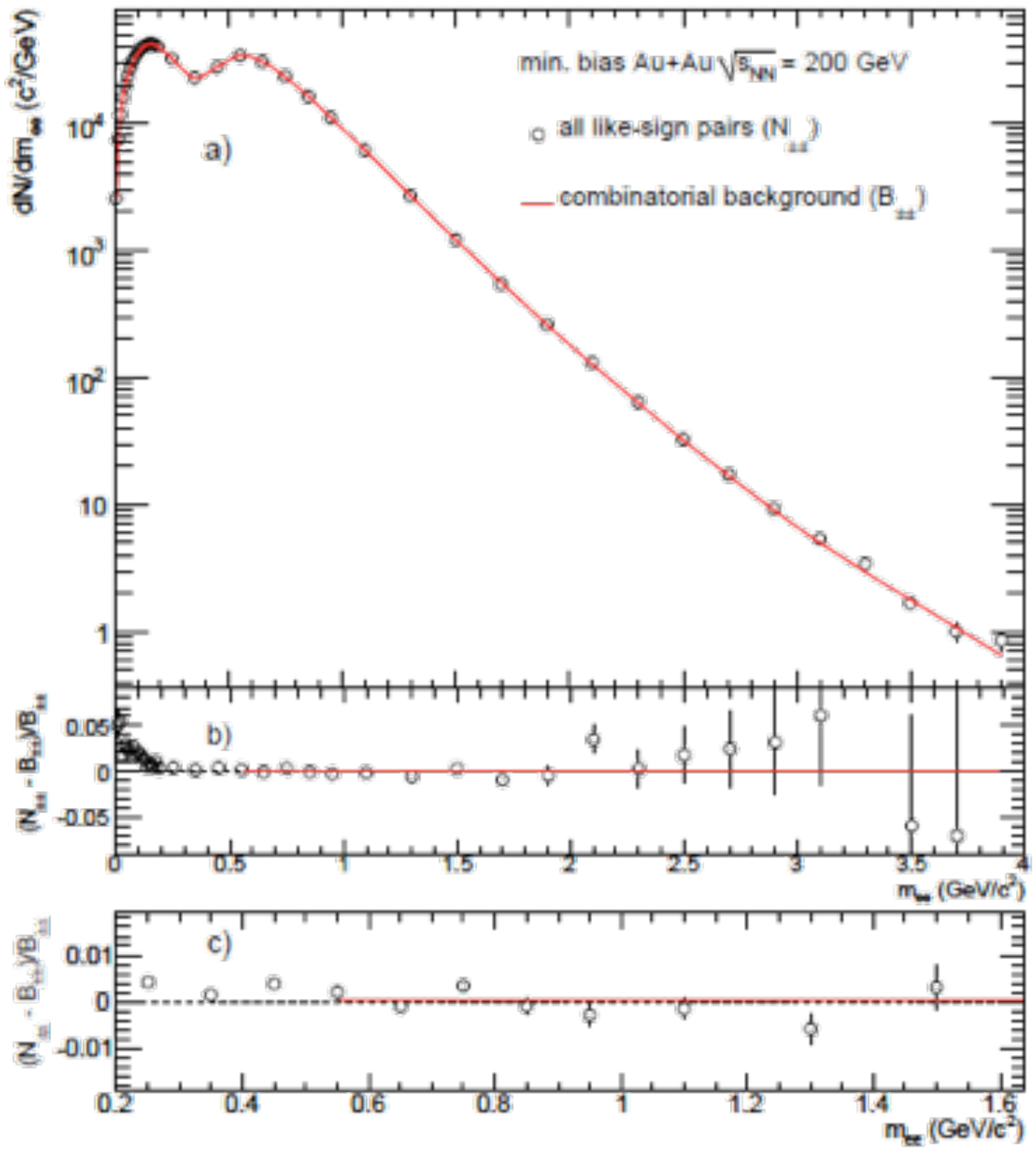
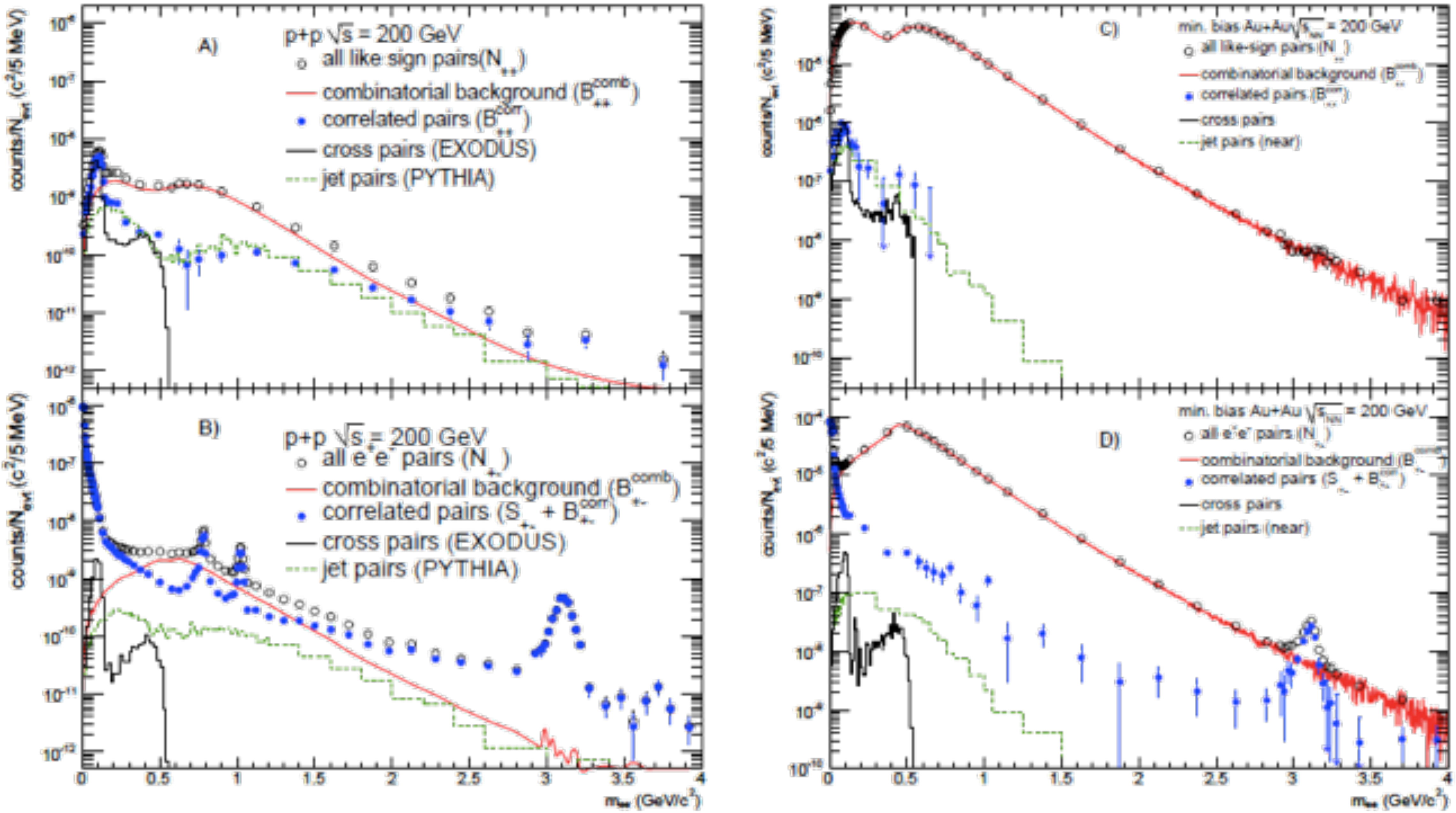
Combinatorial Background Shape

- Shape determined with event mixing
  - Excellent agreements for like-sign pairs
- Normalisation of mixed pairs
  - Small correlated background at low masses
  - Normalise B_{++} and B_{--} to N_{++} and N_{--} for $m_{ee} > 0.7$ GeV/c^2
  - Normalise mixed B_{+-} pairs to $N_{+-} = 2\sqrt{N_{++}N_{--}}$
  - Subtract correlated background
- Systematic uncertainties
  - Statistics of N_{++} and N_{--}: 0.12%
  - Different pair cuts in like- and unlike-sign: 0.2%

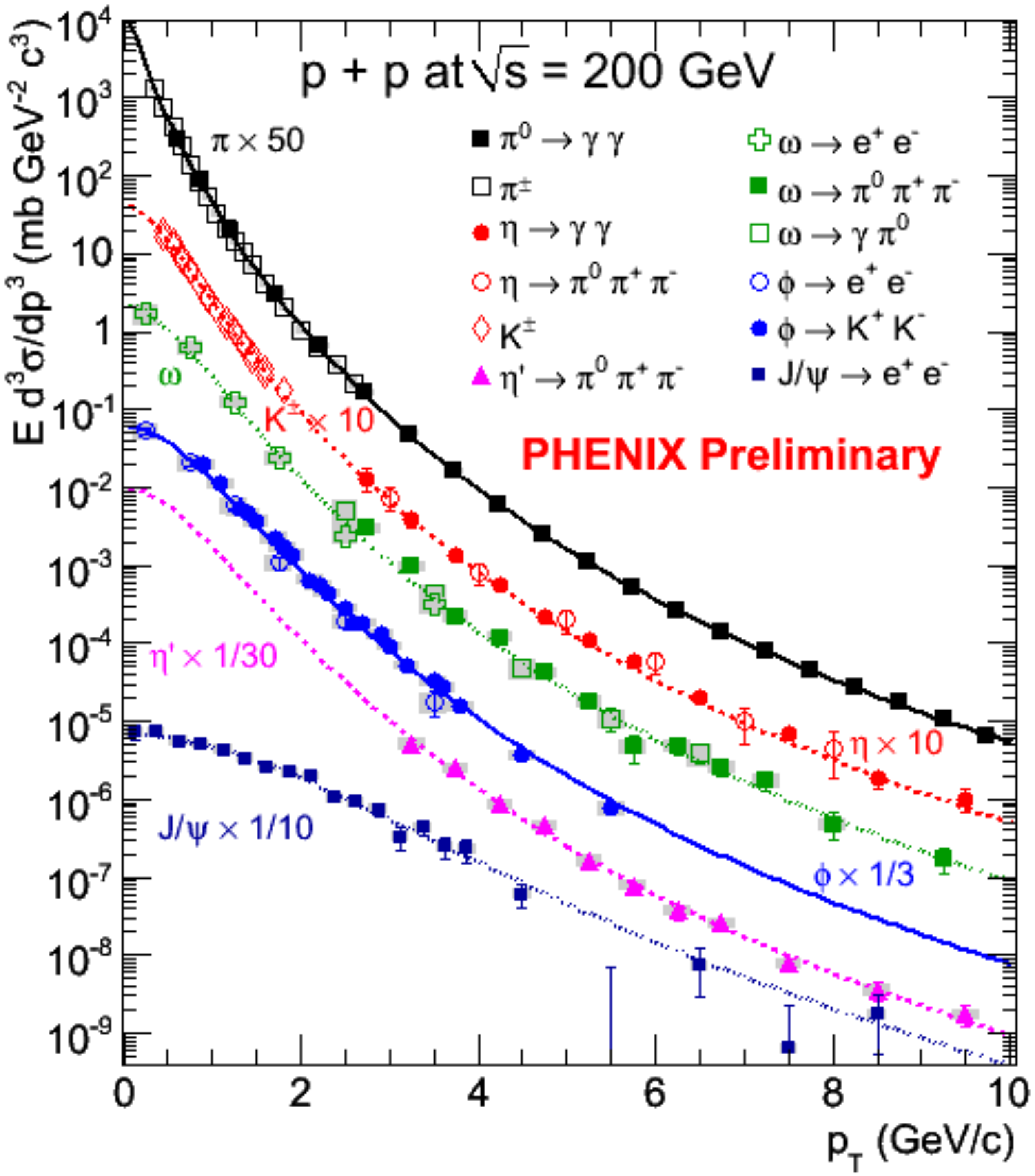


Combinatorial and Correlated



- Combinatorial Background from mixed events normalized to $2\sqrt{N_{++}N_{--}}$
- Cross pairs simulated with decay generator EXODUS
- Jet pairs simulated with PYTHIA

Hadronic Cocktail

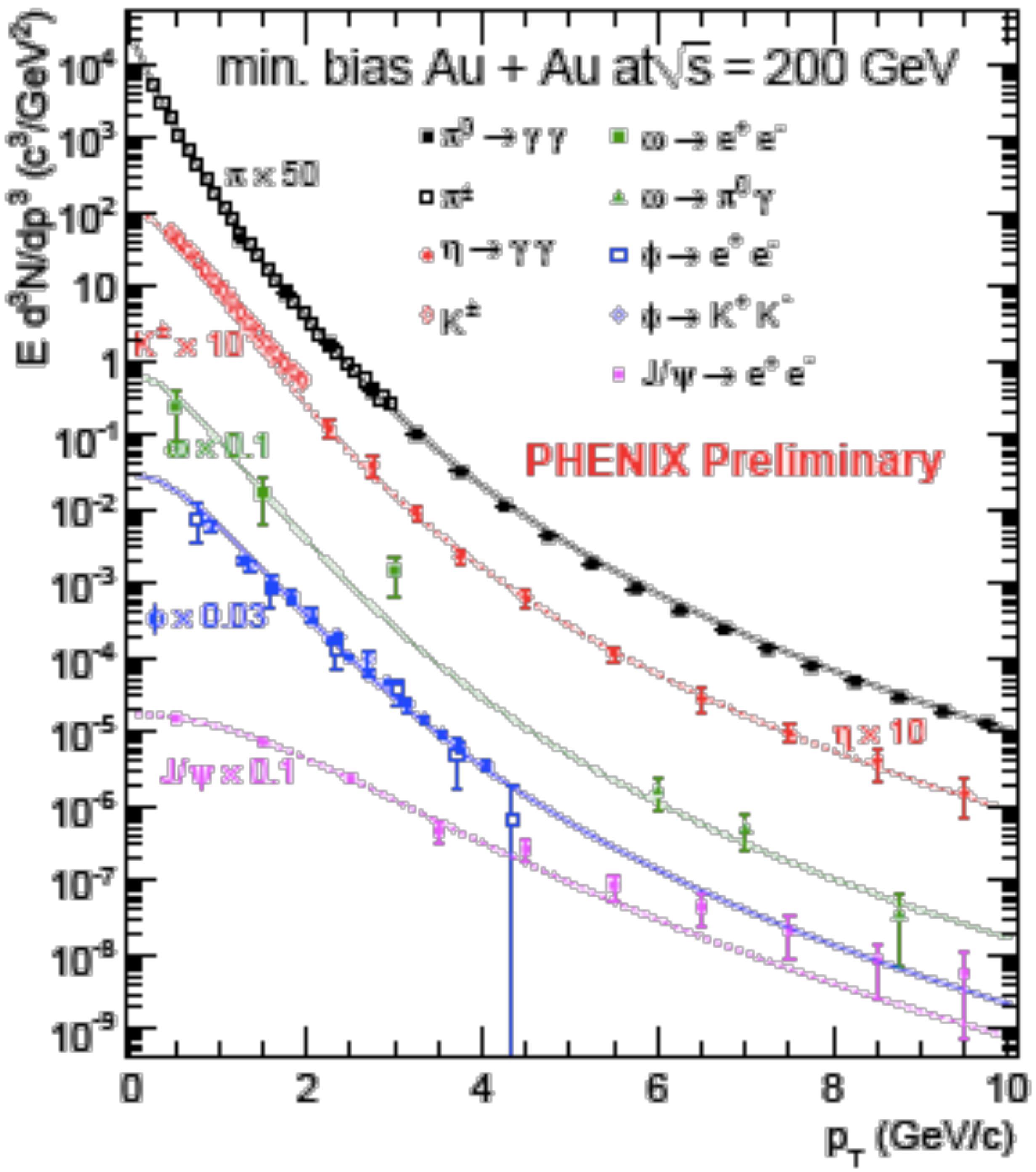


- Parameterization of PHENIX $\pi^\pm$, π^0 data $\pi^0 = (\pi^+ + \pi^-)/2$

$$E\frac{d^3\sigma}{dp^3} = \frac{A}{\left(\exp(-ap_T - bp_T^2) + p_T/p_0\right)^n}$$

- Other mesons: fit with m_T scaling of π^0
  $p_T \to \sqrt{(p_T^2 + m_{meson}^2 - m_\pi^2)}$
  fit the normalisation constant
- All mesons m_T scale!
- Hadronic cocktail was well tuned to individually measured yield of mesons in PHENIX for both p+p and Au+Au collisions
- Mass distributions from hadron decays are simulated by Monte Carlo: π^0, η, η', ω, φ, ρ, J/ψ, ψ'

Hadronic Cocktail



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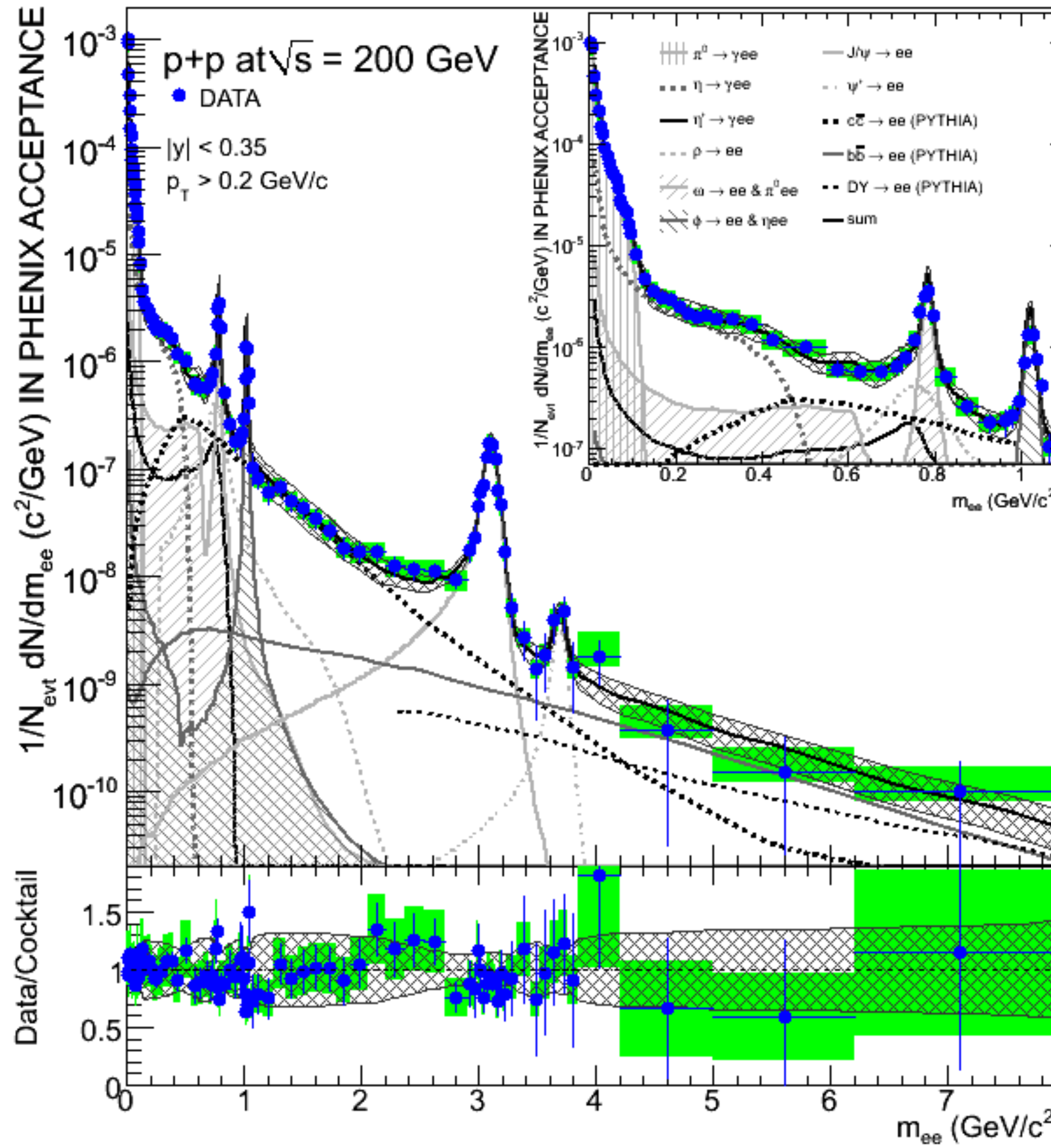
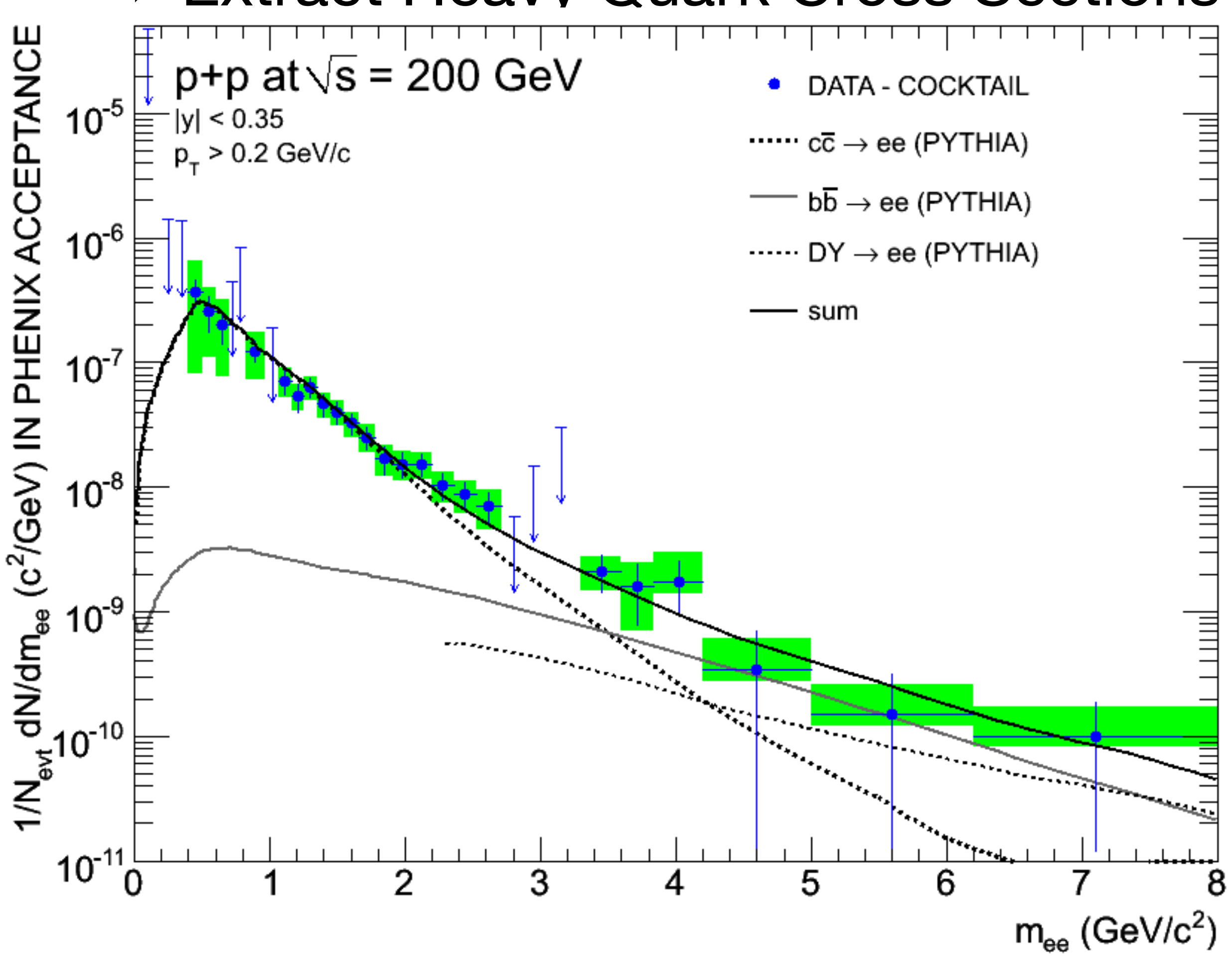
p+p at √s = 200 GeV

PLB 670 (2009) 313

- Data absolutely normalised
- Excellent agreement with Cocktail
    - Filtered in PHENIX acceptance



- Light hadron contributions subtracted
    - Extract Heavy Quark Cross Sections



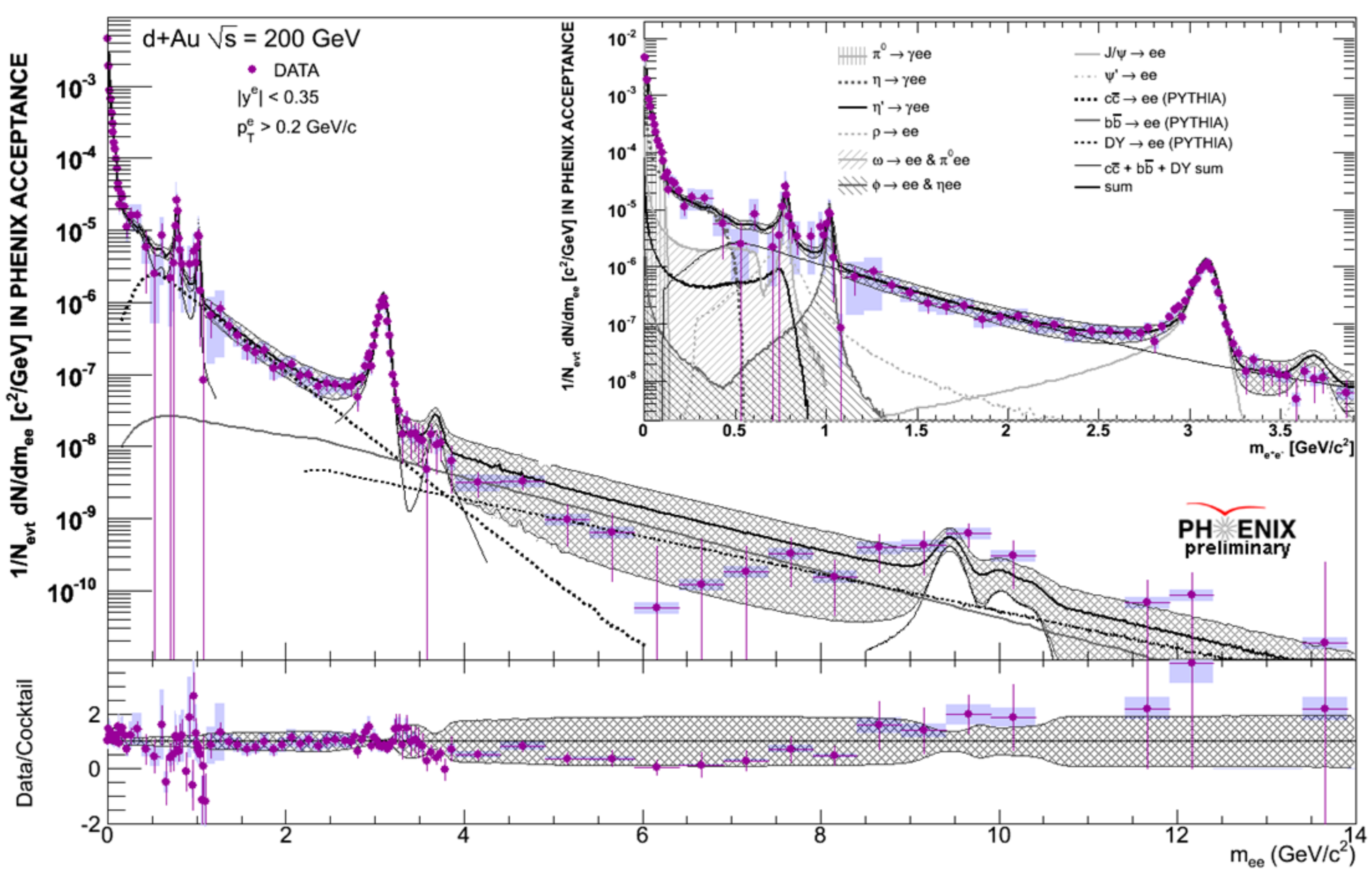
$$\sigma_{c\bar{c}} = 518 \pm 47(\mathrm{stat}) \pm 135(\mathrm{syst}) \pm 200(\mathrm{model})\ \mu\mathrm{b}$$

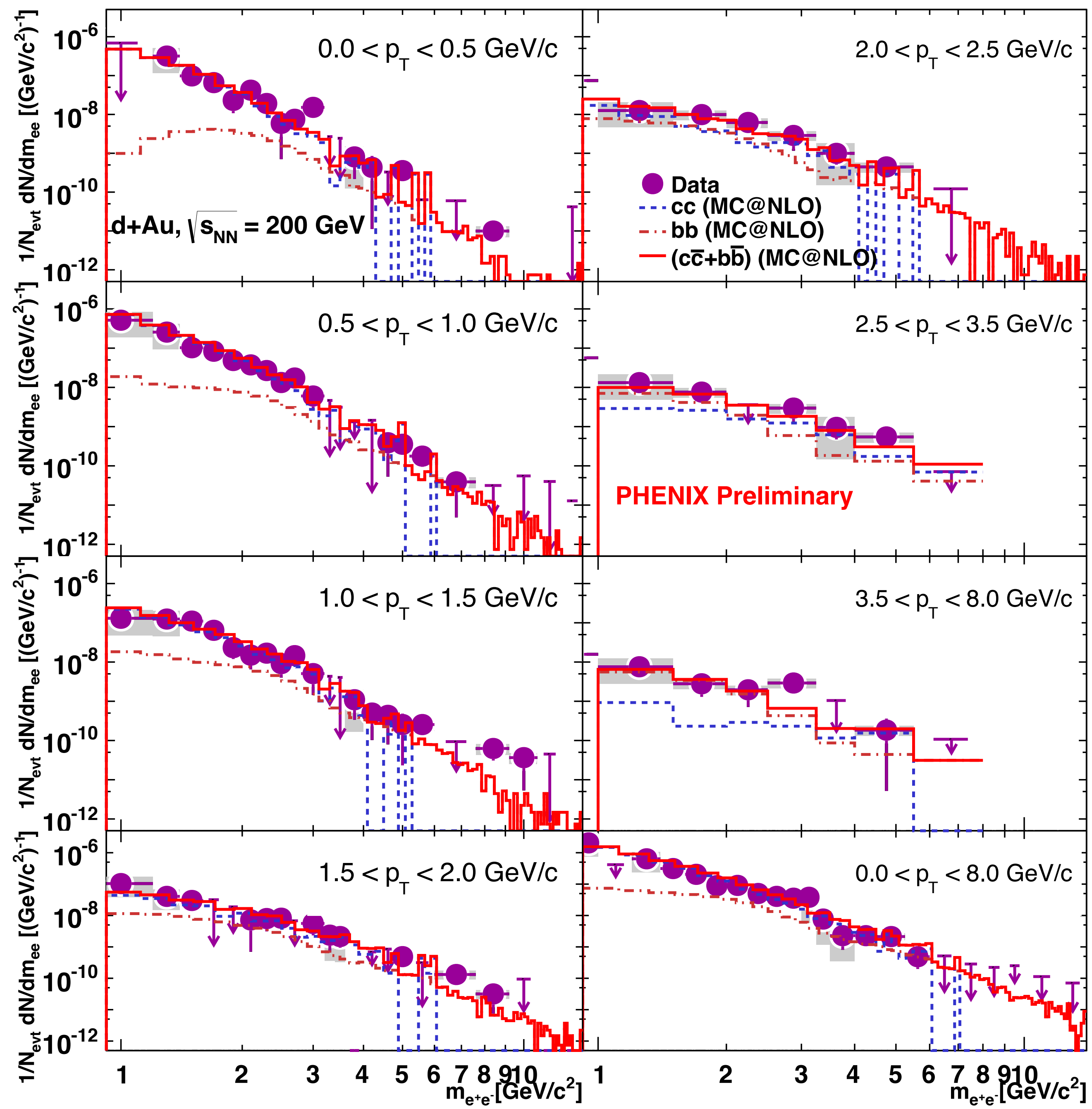
$$\sigma_{b\bar{b}} = 3.9 \pm 2.4(\mathrm{stat})^{+3}_{-2}(\mathrm{syst})\ \mu\mathrm{b}$$

d+Au at $\sqrt{s_{NN}}$ = 200 GeV

D. Sharma, Hard Probes 2013

- Data consistent with cocktail
  - No significant cold nuclear matter effects
- Extract charm and beauty in mass & p_T
  - $\sigma_{c\bar{c}}^{NN}$ = 704 ± 47 (stat) ± 183 (syst) ± 40 (model) μb
  - $\sigma_{b\bar{b}}^{NN}$ = 4.29 ± 0.39 (stat) ± 1.08 (syst) ± 0.11 (model) μb

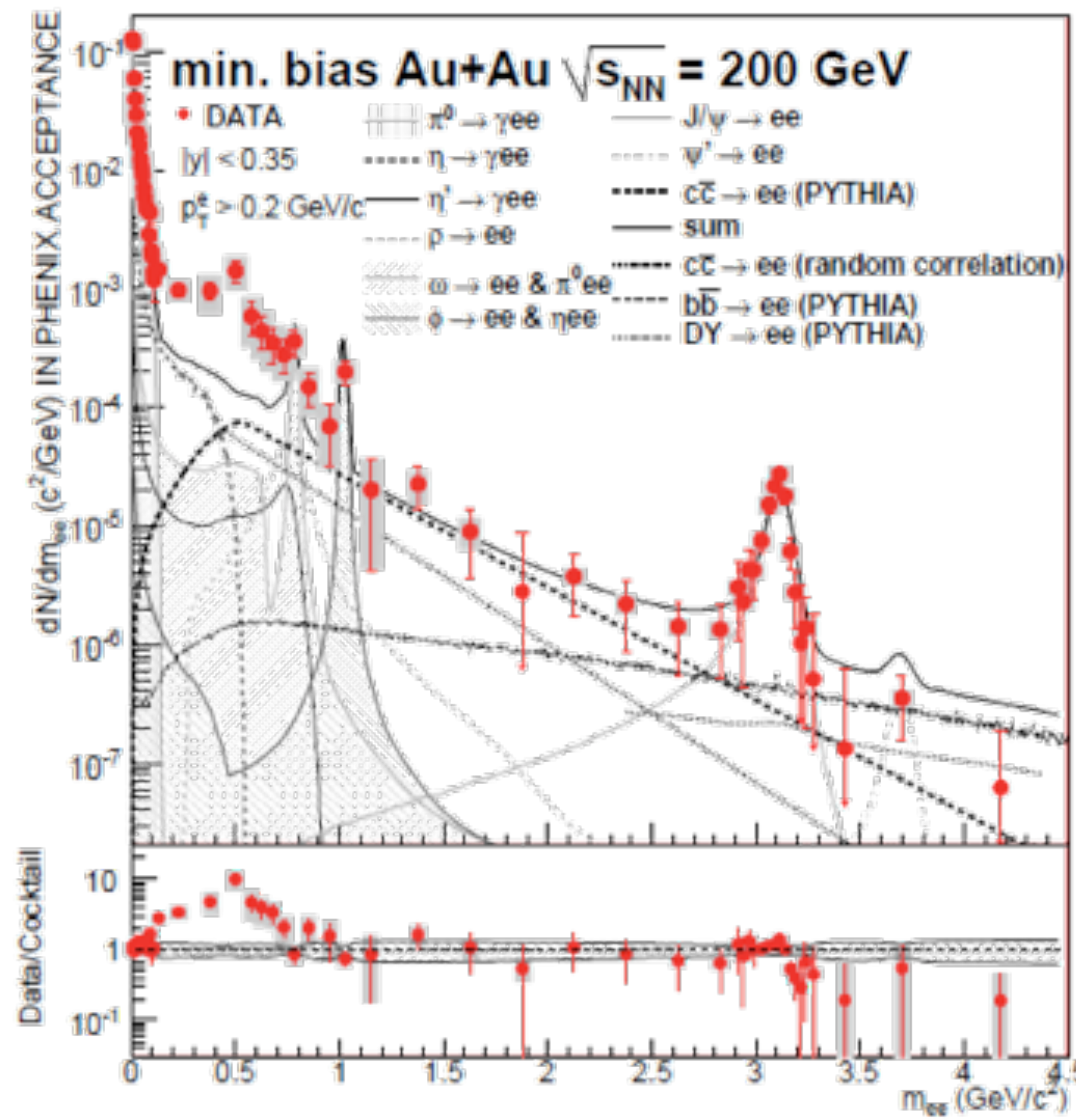




Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

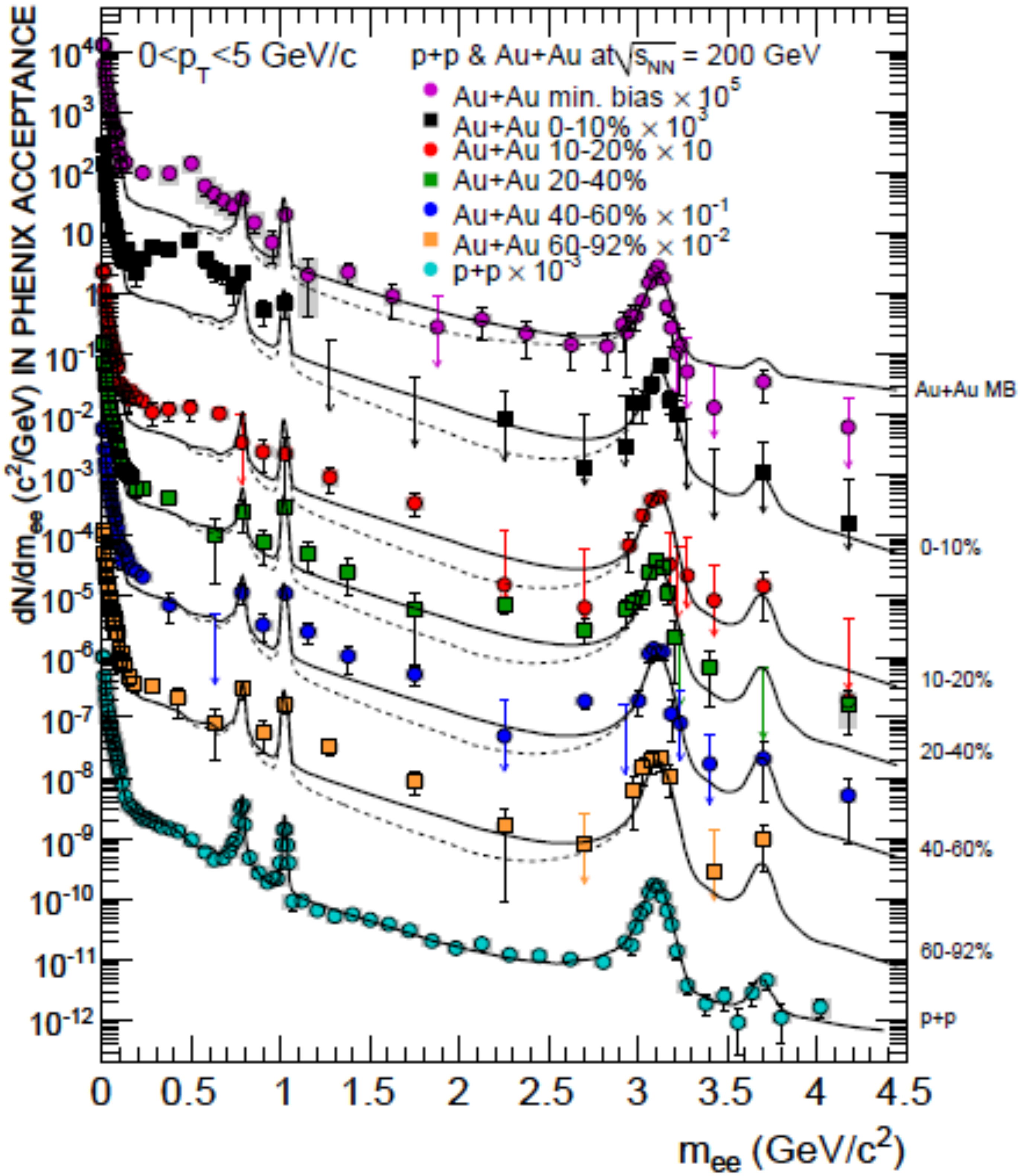
PRC 81 (2010) 034911

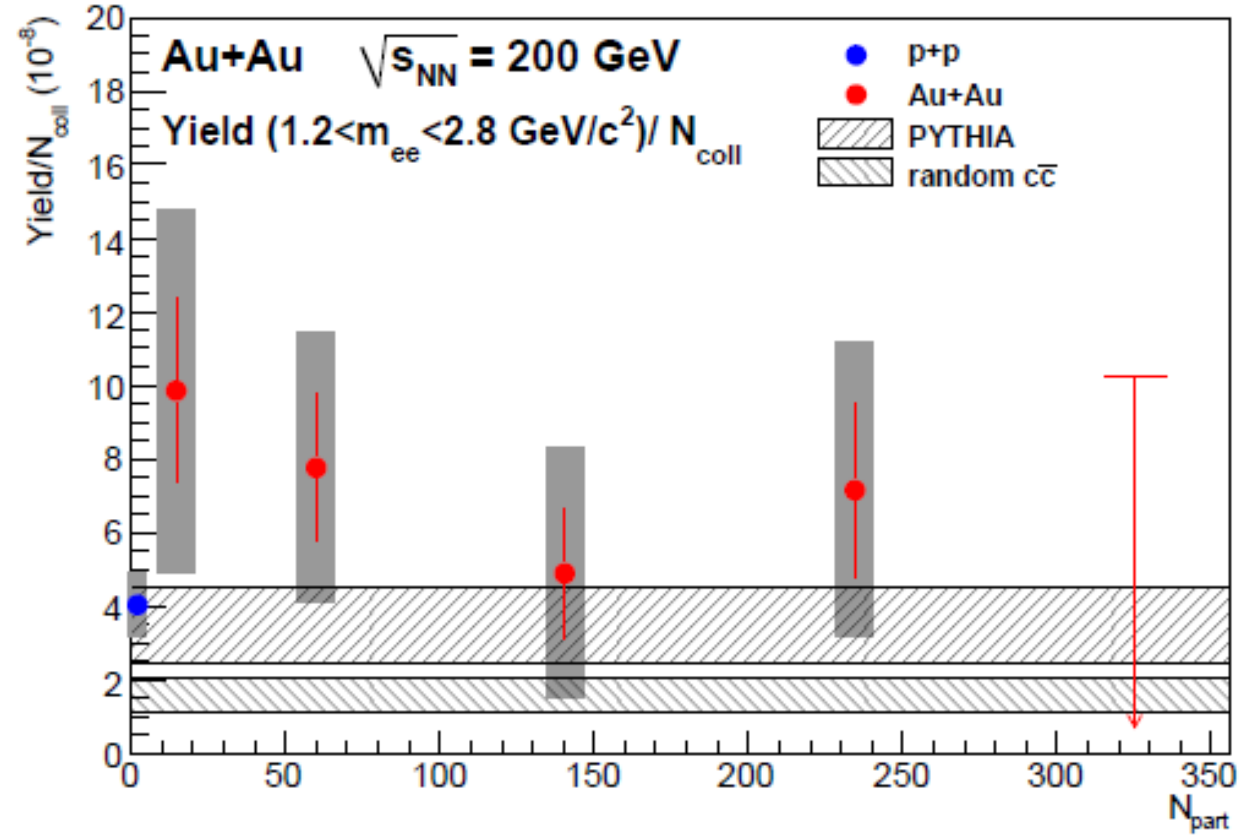
- Low Mass Region:
  enhancement $150 < m_{ee} < 750$ MeV/c^2
  - 4.7 ± 0.4(stat) ± 1.5(syst) ± 0.9(model)
- Intermediate Mass Region:
  dominated by charm ($N_{coll} \times \sigma_{cc}$)
  - PYTHIA
  - Random $c\bar{c}$ correlation
- Single electron measurement:
  - High p_T suppression
  - Flow
- Expected modifications in the pair invariant mass
  - Random $c\bar{c}$ correlation?
- Room for thermal contribution?



Centrality Dependence: IMR

PRC 81 (2010) 034911

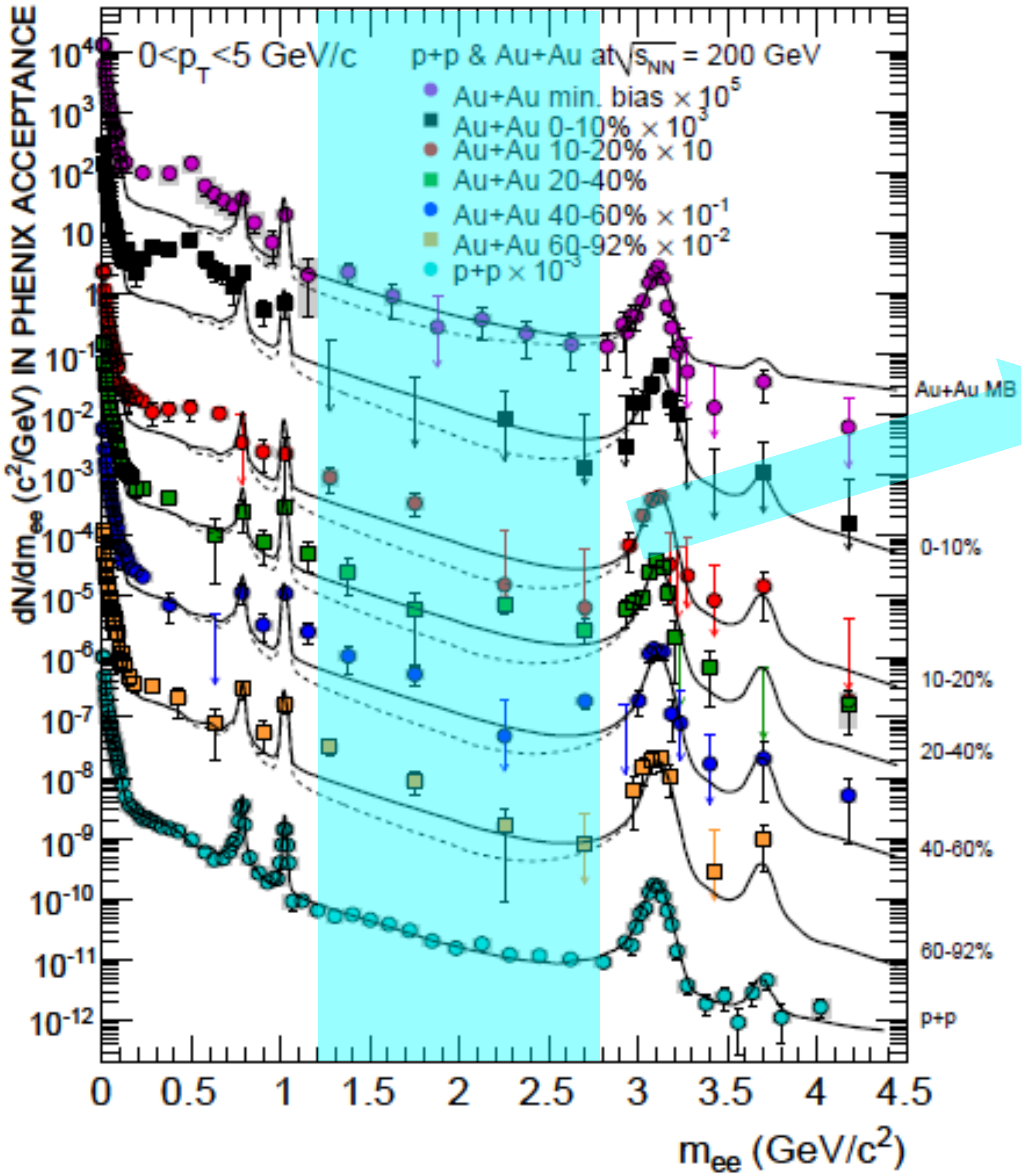


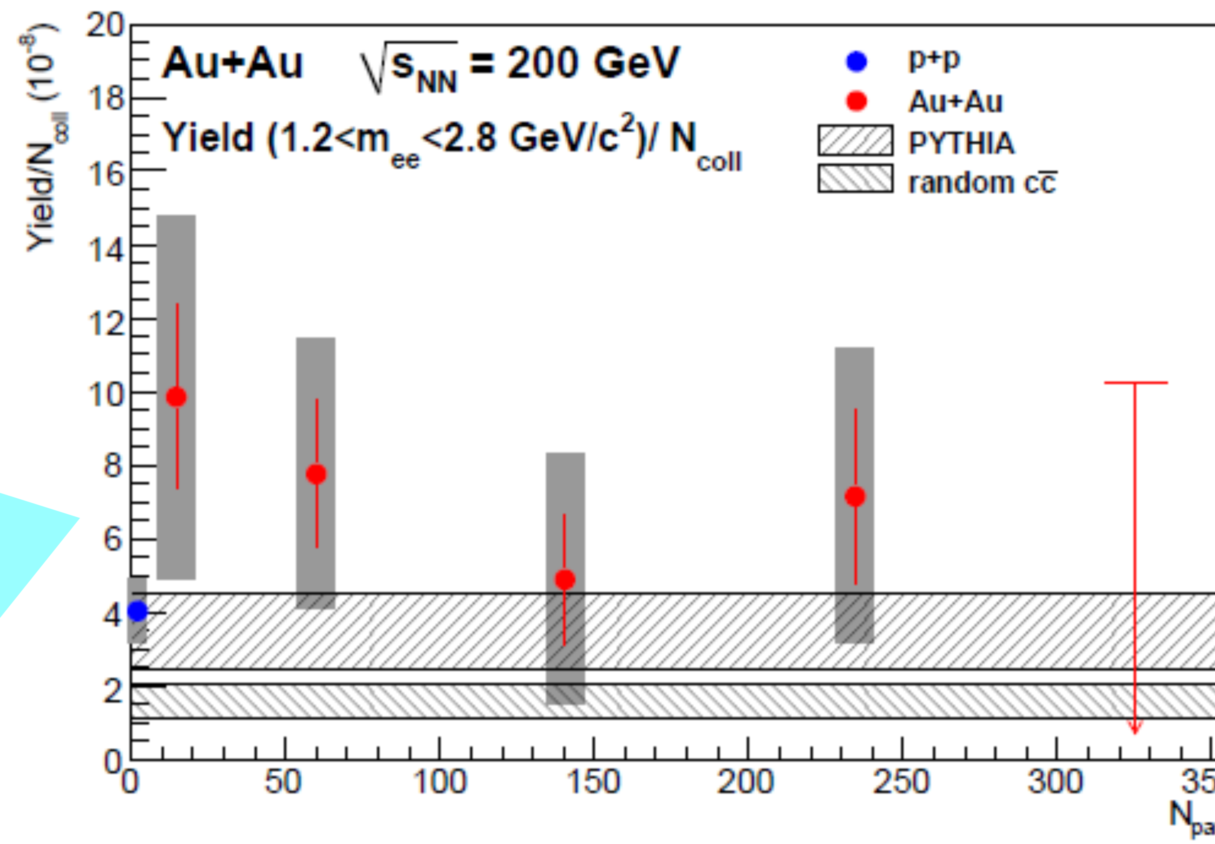


- Charm is a hard probe
  - Total yield follows binary scaling (known from single $e^{\pm}$)
  - Intermediate mass yield shows the same scaling

Centrality Dependence: IMR

PRC 81 (2010) 034911

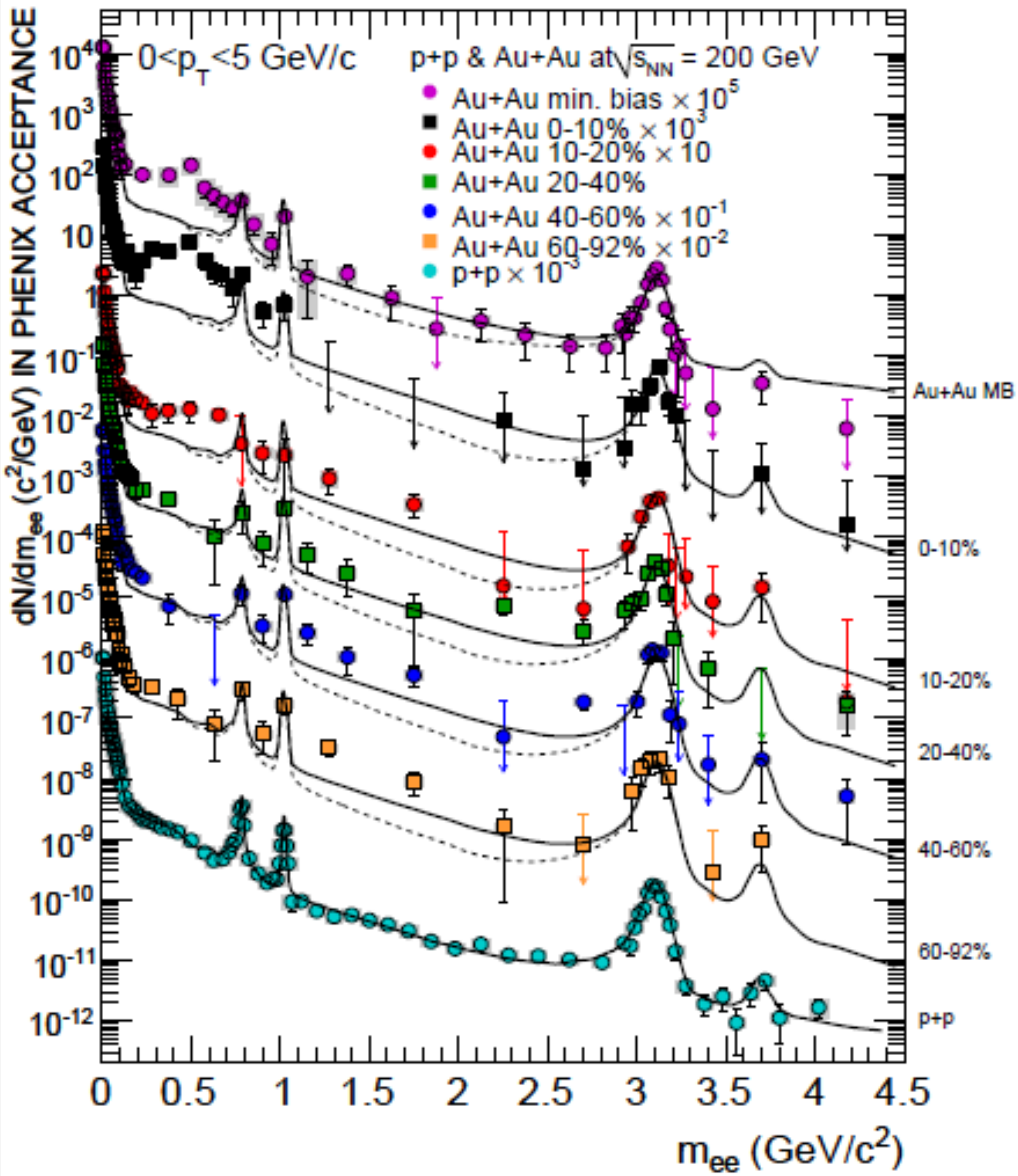




- Charm is a hard probe
  - Total yield follows binary scaling (known from single $e^{\pm}$)
  - Intermediate mass yield shows the same scaling

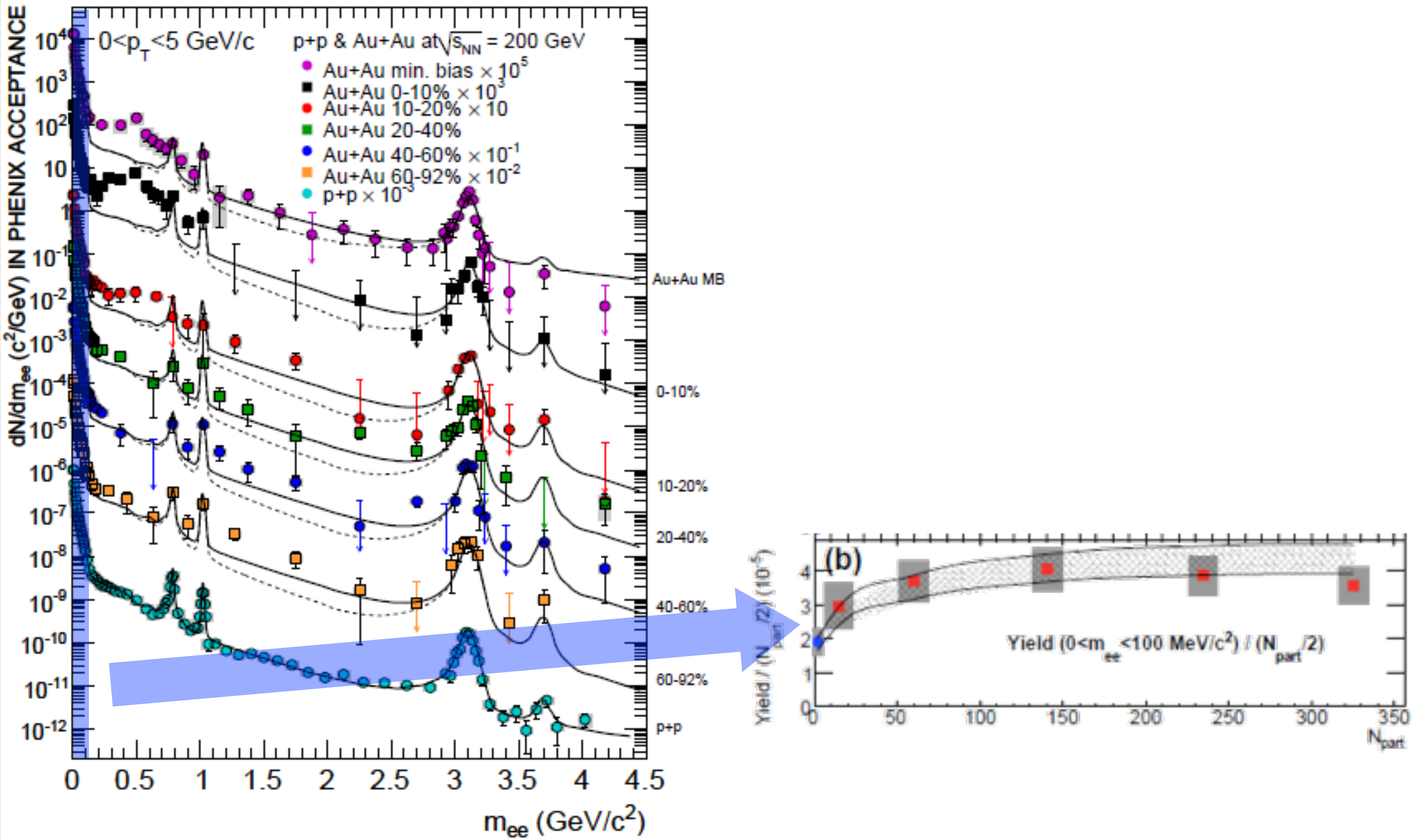
Centrality Dependence: LMR

PRC 81 (2010) 034911



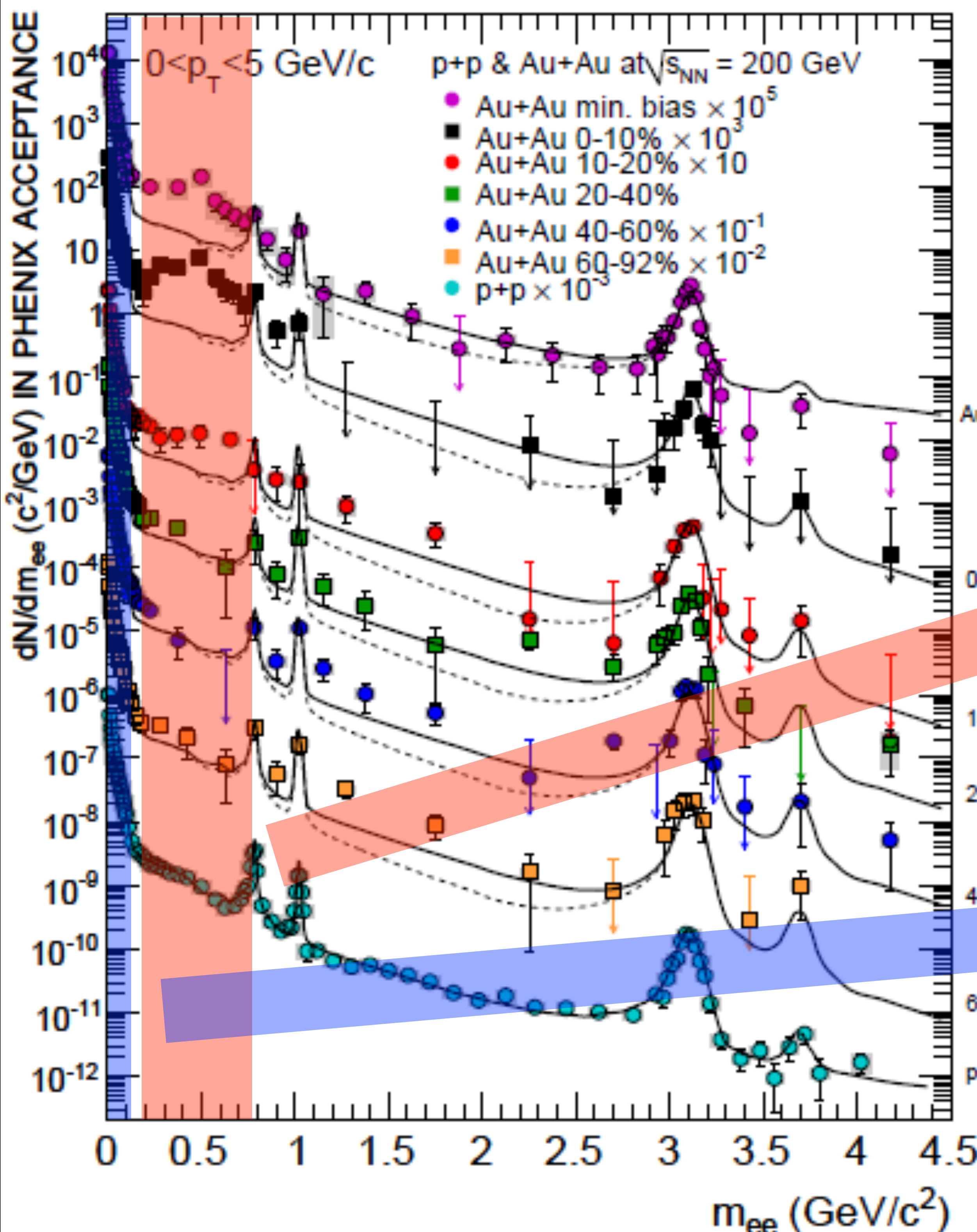
Centrality Dependence: LMR

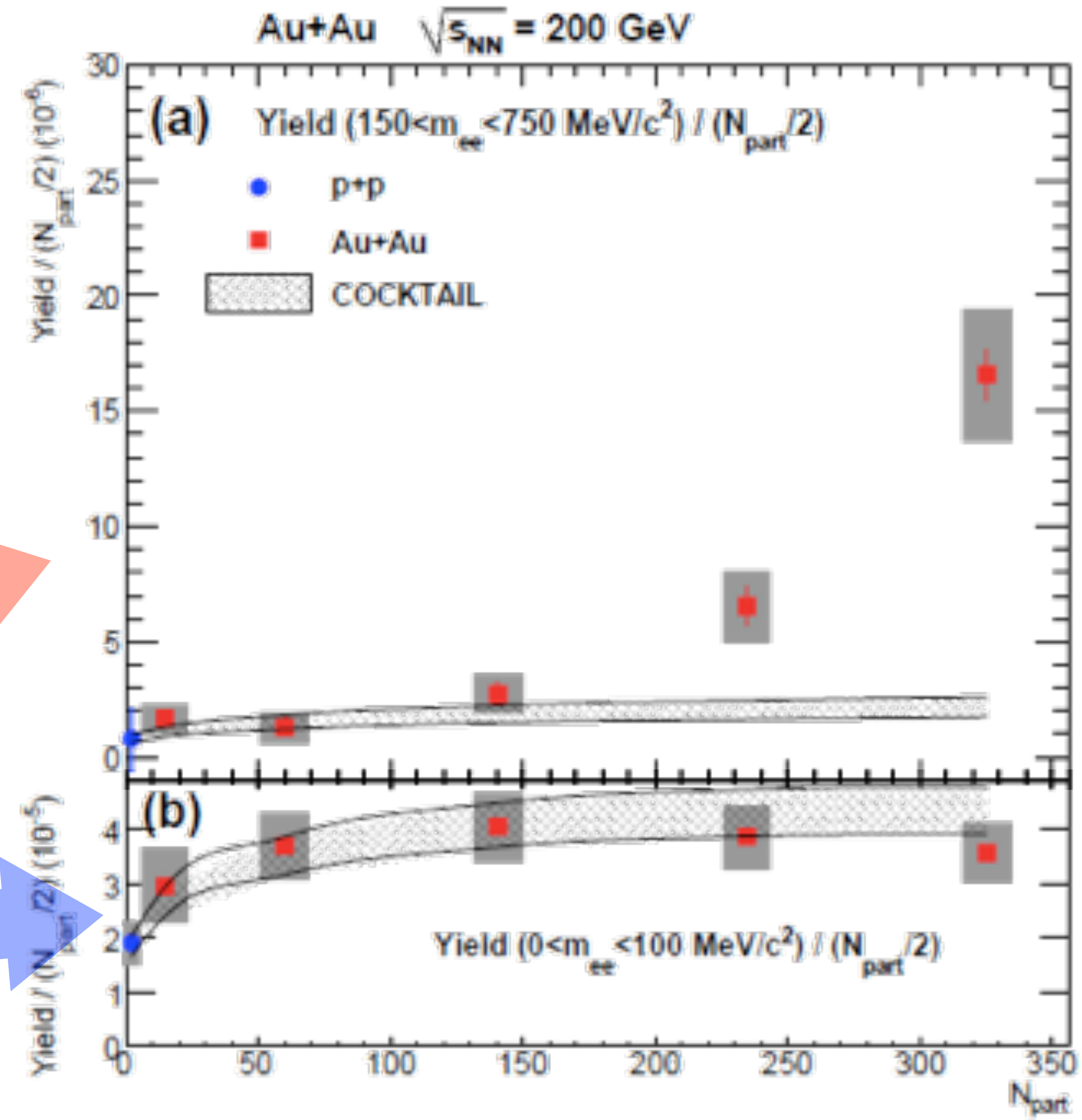
PRC 81 (2010) 034911



Centrality Dependence: LMR

PRC 81 (2010) 034911

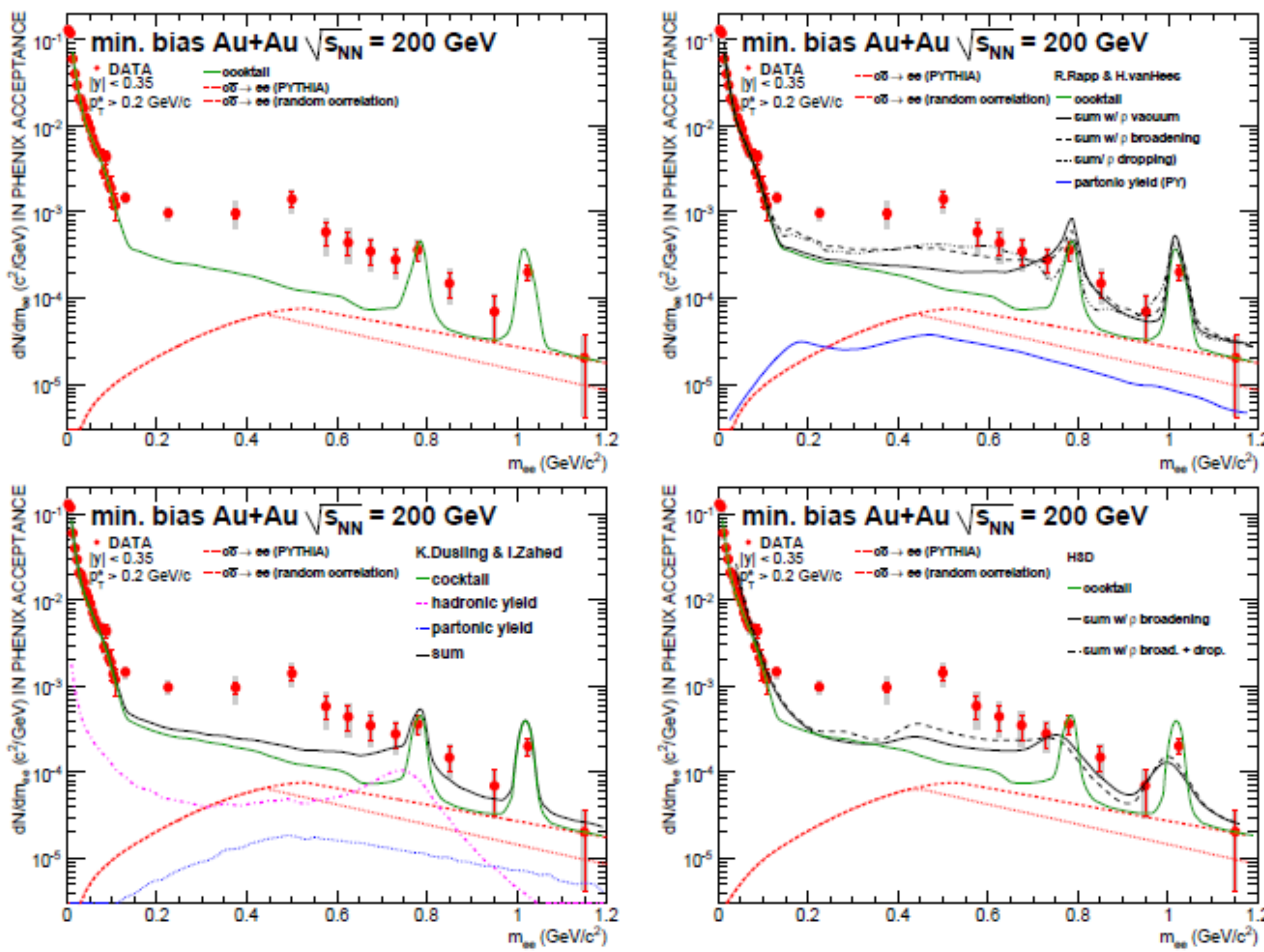




Model Comparison

PRC 81 (2010) 034911

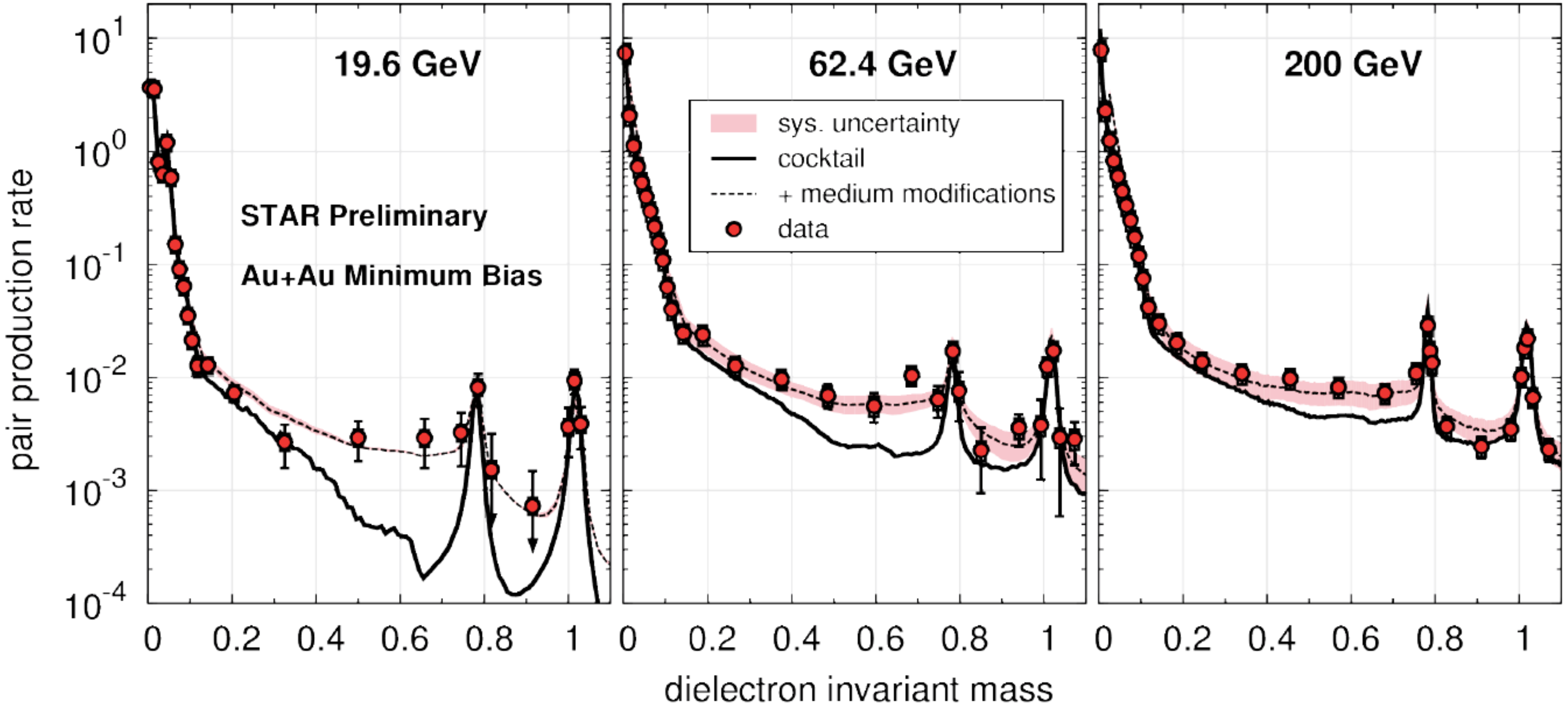
- ππ annihilation + modified ρ spectral function
  - Broadening
  - Mass shifting
  - Both
- Insufficient to explain data



Low Mass Dileptons from STAR

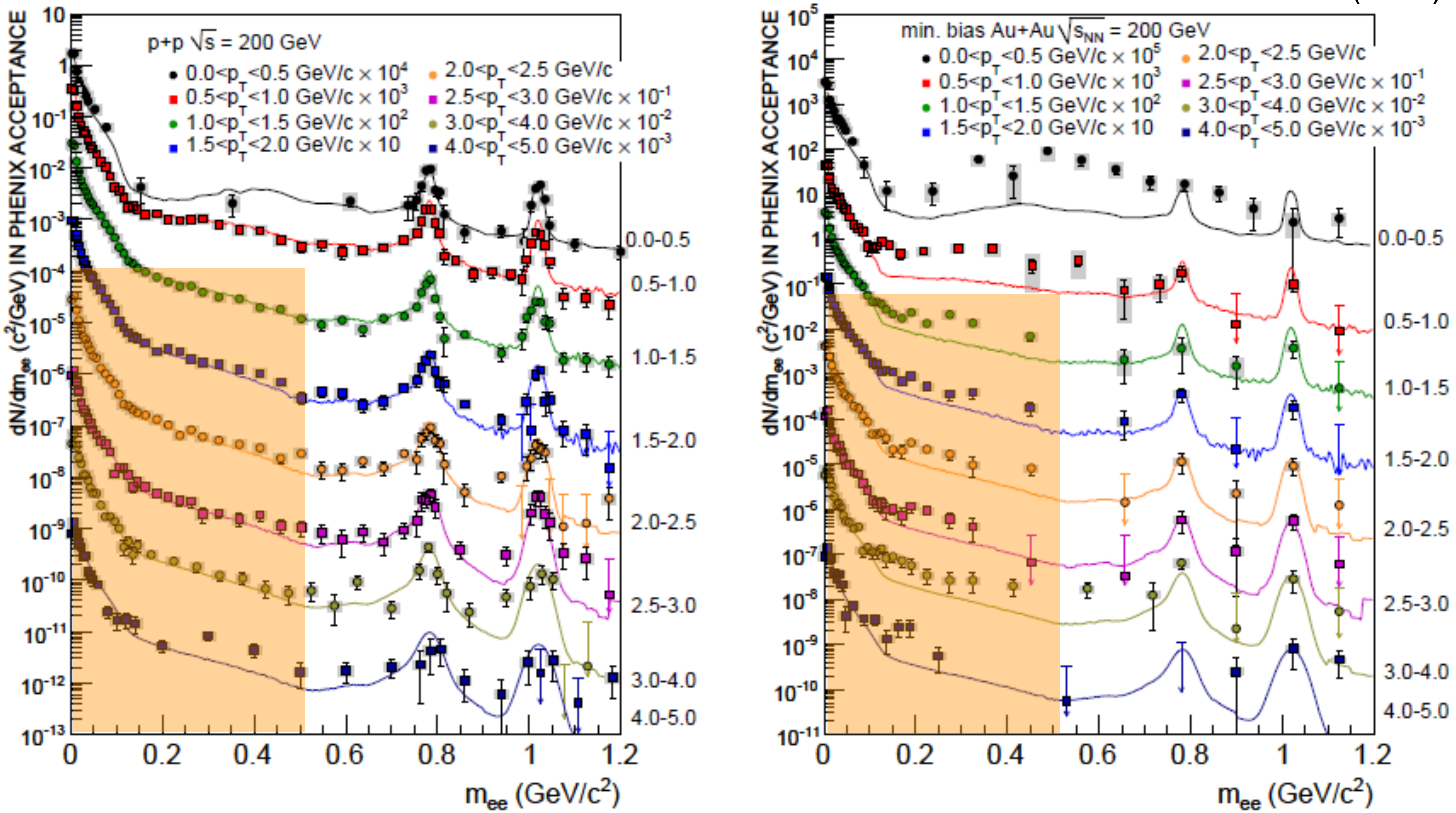
J. Butterworth, Hard Probes 2013

- STAR measured low mass dileptons at three $\sqrt{s_{NN}}$
- STAR observes smaller enhancement than PHENIX
  - In better agreement with models that involve broadening of ρ spectral function
- Waiting for results from PHENIX HBD data



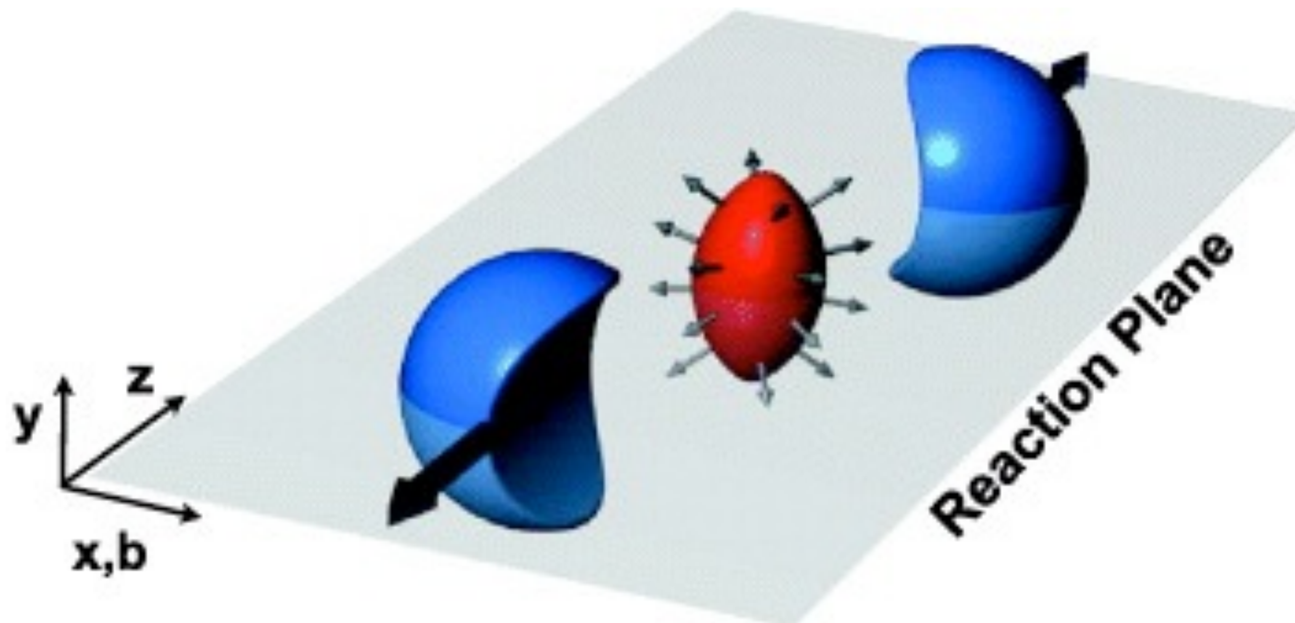
Momentum Dependence: PHENIX

PRC 81 (2010) 034911

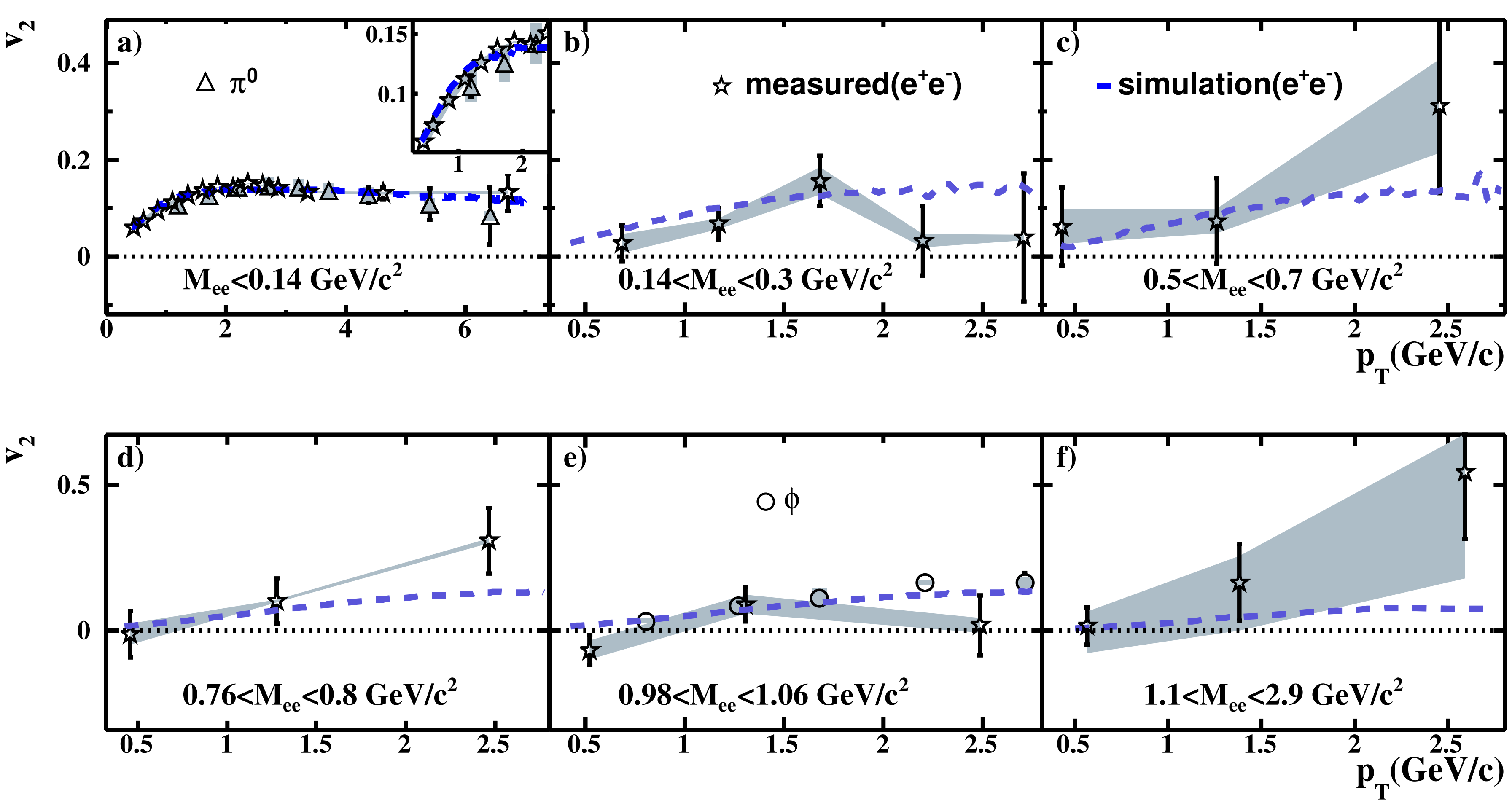


- p+p in agreement with cocktail
- Au+Au low mass enhancement concentrated at low p_T

STAR: Azimuthal Anisotropy



- Initial anisotropy in collision geometry → pressure gradient causes momentum anisotropy
- Fourier decomposition:
  - second coefficient: v_2 (elliptic flow)
- v_2 of dielectrons (including enhancement) consistent with hadronic cocktail v_2

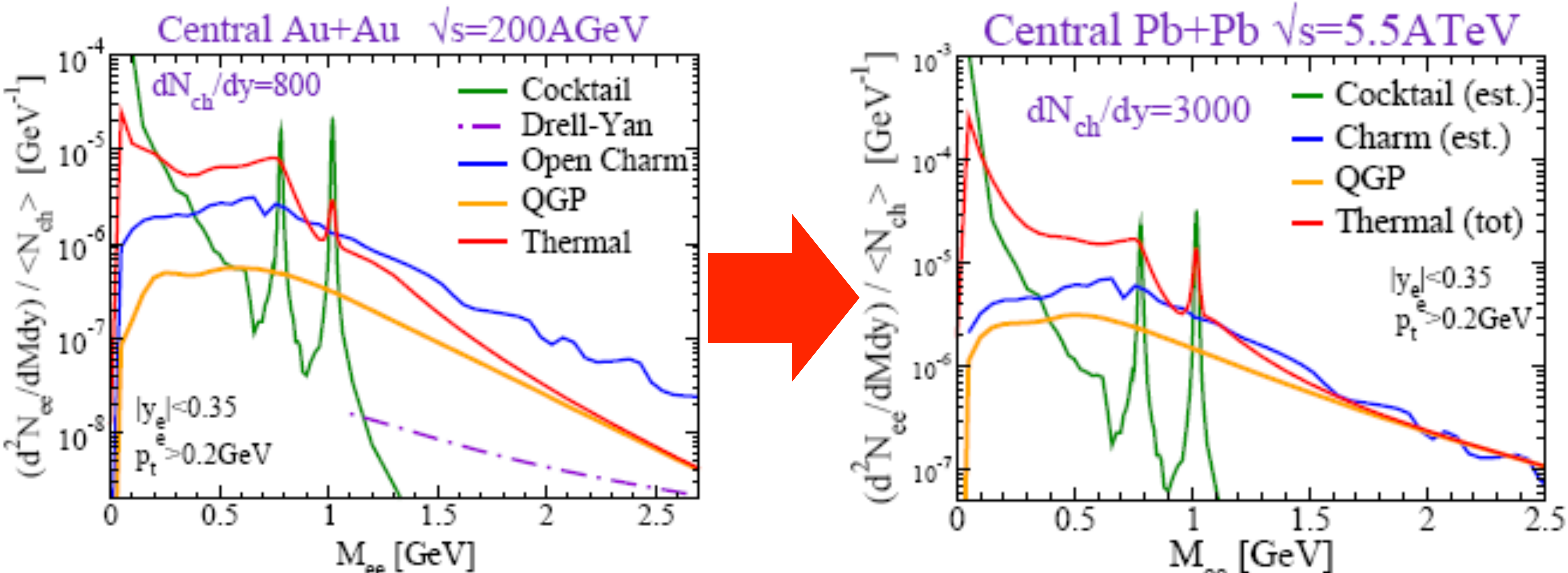


LHC

The Large Hadron Collider

Expectations at the LHC

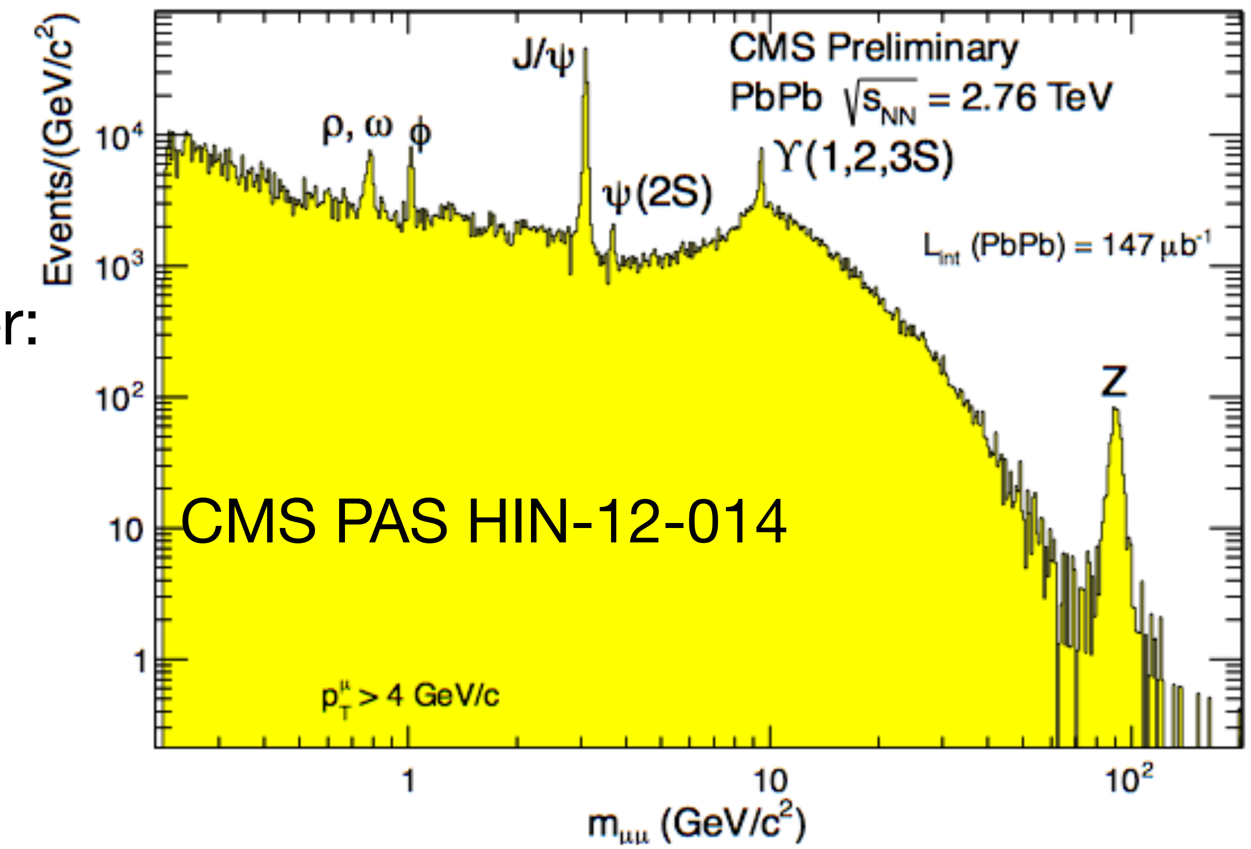
- With higher dN/dy thermal radiation from hadron gas dominant for m<1GeV
- For m>1GeV stronger QGP radiation:
  - comparable to DD but be does not include charm energy loss



H. van Hees and R.Rapp

Low mass dileptons at the LHC

- CMS or ATLAS:
    - good mass resolution and vertexing
    - but: large magnetic field and absorber:
        - single muon p_{min} ~ 3–5 GeV/c
    - cannot measure at low p_T
- ALICE:
    - the only LHC experiment that can measure dileptons at low p_T
    - Letter of Intent:
        - dedicated lower B-field run



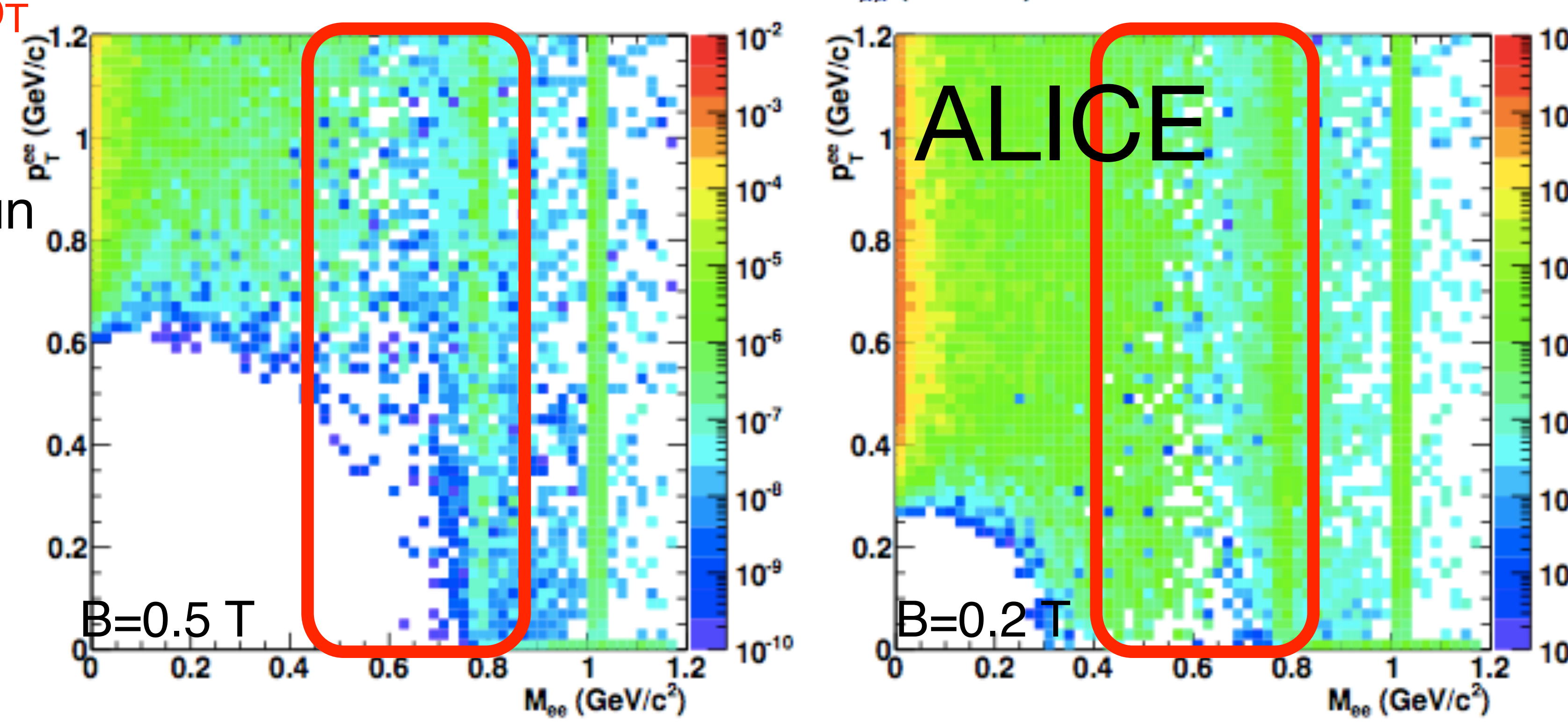


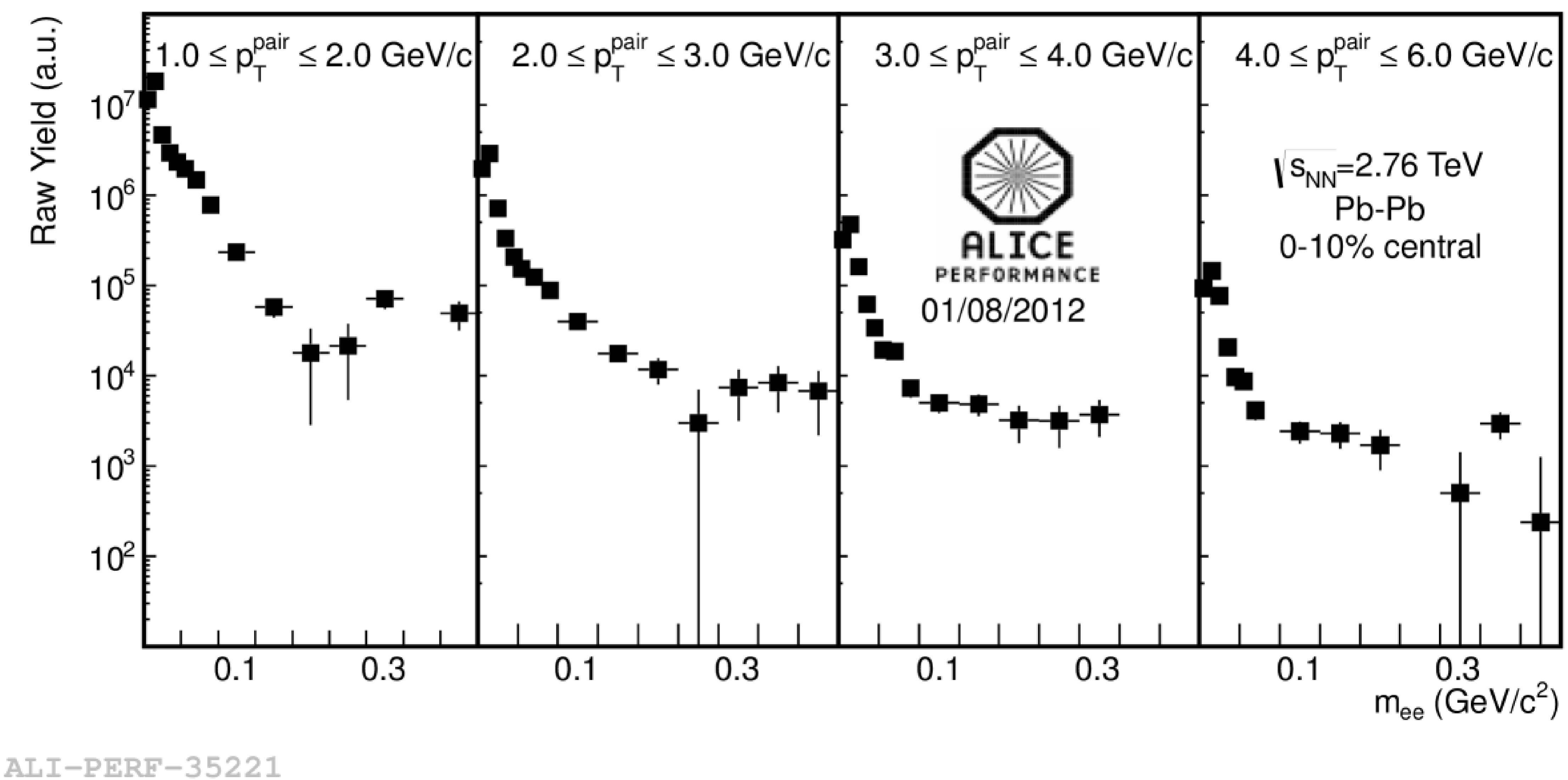
Figure 2.45: Acceptance for e^+e^--pairs from PYTHIA at $B = 0.5$ T (left) and $B = 0.2$ T (right).

ALICE, Letter of Intent, LHCC-I-022

Low Mass Dileptons in ALICE: Status

A. Uras, Hard Probes 2013

- Challenging electron identification:
  - Time Projection Chamber and Time Of Flight
- S/B ratio of few ‰ in the lowest p_T bin:
  - accurate combinatorial background evaluation needed
- Analysis ongoing

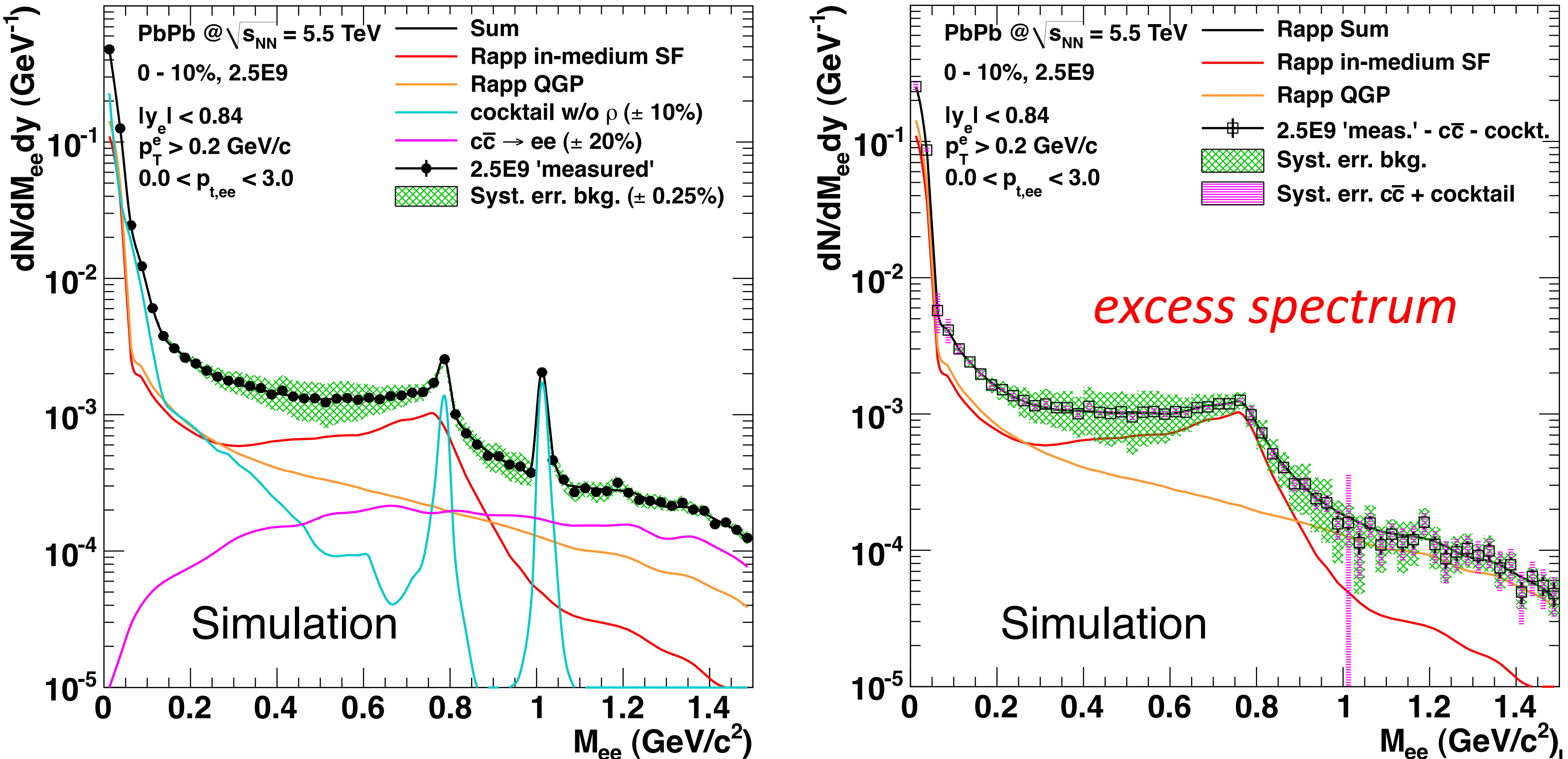


Low Mass Dileptons in ALICE: Future

- TPC and ITS upgrades:
  - allow high data rates
  - reduce charm background with dca cut
- Dedicated low B-field run (B=0.2 T)

H. Appelshäuser, ECT* dilepton workshop 2013

2.5×10^9 events = “1 year” at 50 kHz



Summary

- EM probes ideal “penetrating probes” of dense partonic matter created at RHIC and the LHC
  - also at the SPS?
- Double differential measurement of dilepton emission rates can provide
  - Temperature of the matter
  - Medium modification of EM spectral function
- But extremely challenging measurements

SPS results:

- CERES and NA60 see enhancement in LMR
- NA60 measured ρ spectral function:
  - favours broadening over dropping mass scenario
  - observes prompt excess in IMR with inv. slopes close/above to T_c

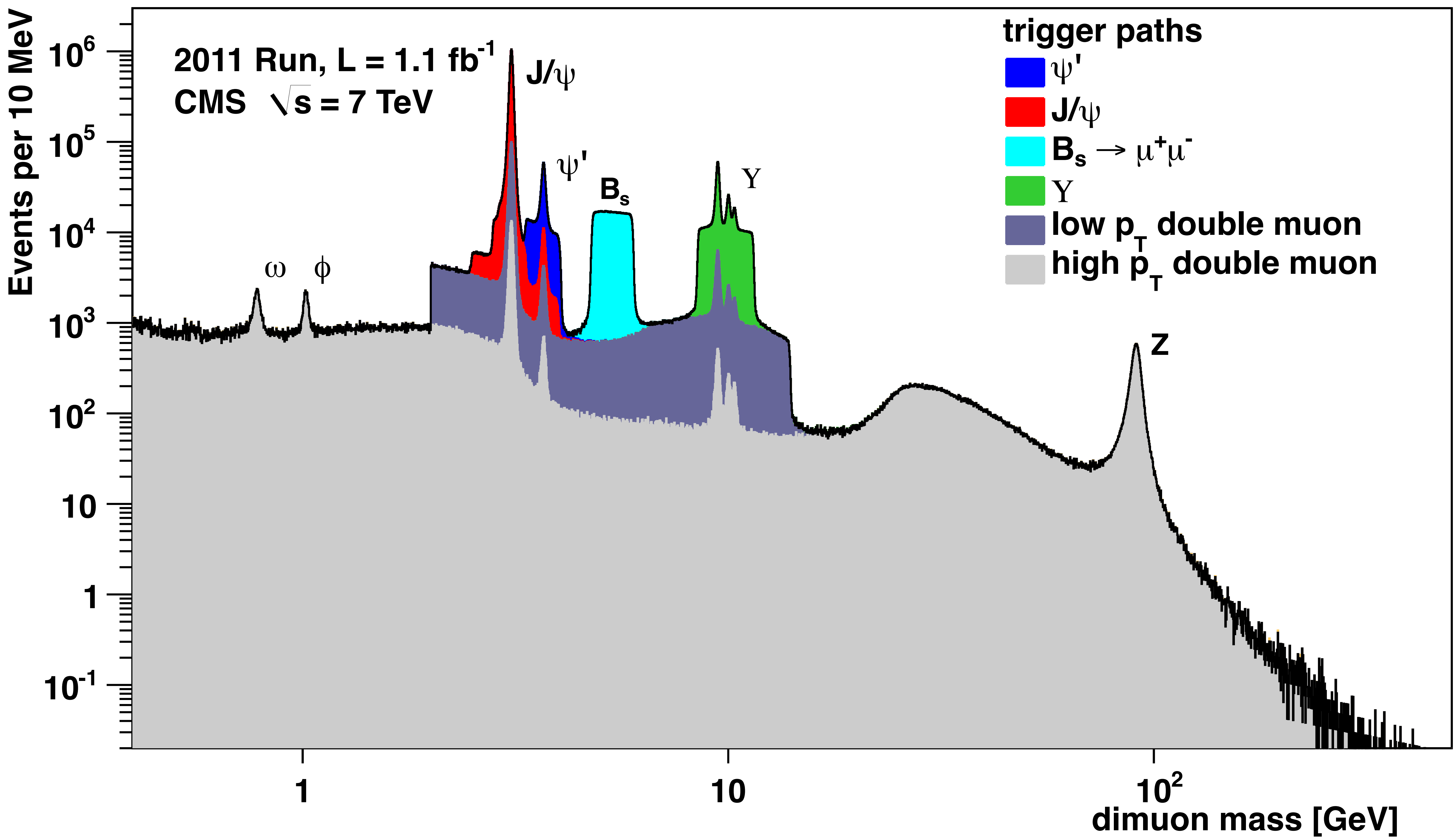
At RHIC:

- PHENIX measured dilepton continuum in p+p, d+Au and Au+Au:
  - In p+p and d+Au: good agreement between data and hadronic cocktail
    - measured charm and beauty cross section in IMR and HMR
  - In Au+Au: low p_T and low mass enhancement above hadronic cocktail
    - 4.7 ± 0.4(stat) ± 1.5(syst) ± 0.9(model)
    - not reproduced by theoretical models
- STAR also measured LMR enhancement
  - smaller than PHENIX, in better agreement with models
  - LMR elliptic flow consistent with hadron v_2

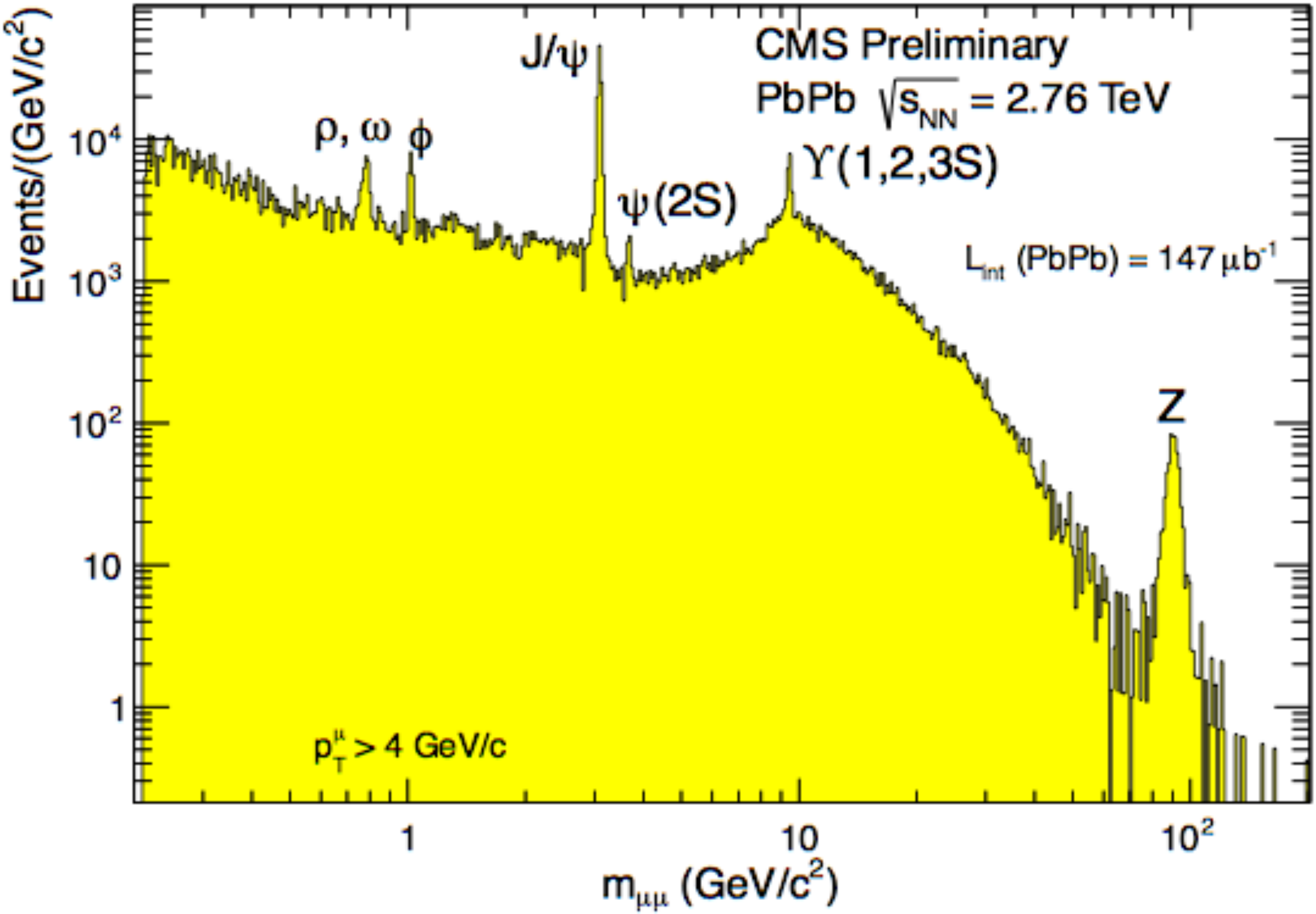
At the LHC:

- first performance studies from ALICE
- need ITS and TPC upgrades for precise measurements (+ low B-field)

Backup

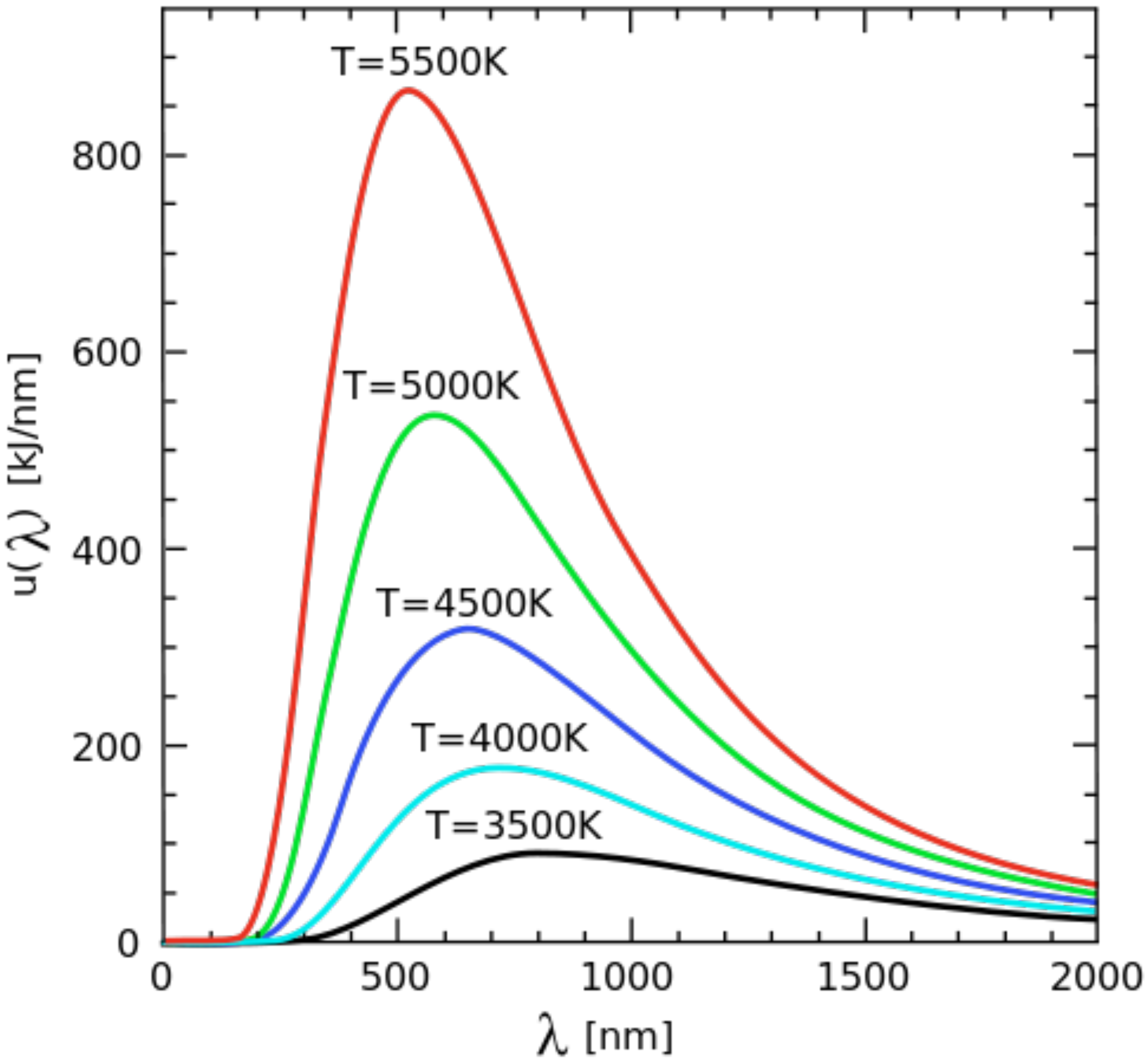


2011 Run, L = 1.1 fb^{-1}
CMS $\sqrt{s}$ = 7 TeV
trigger paths
ψ'
J/ψ
$B_s \rightarrow \mu^+\mu^-$
Υ
low p_T double muon
high p_T double muon
ω
φ
J/ψ
ψ'
B_s
Υ
Z
Events per 10 MeV
dimuon mass [GeV]

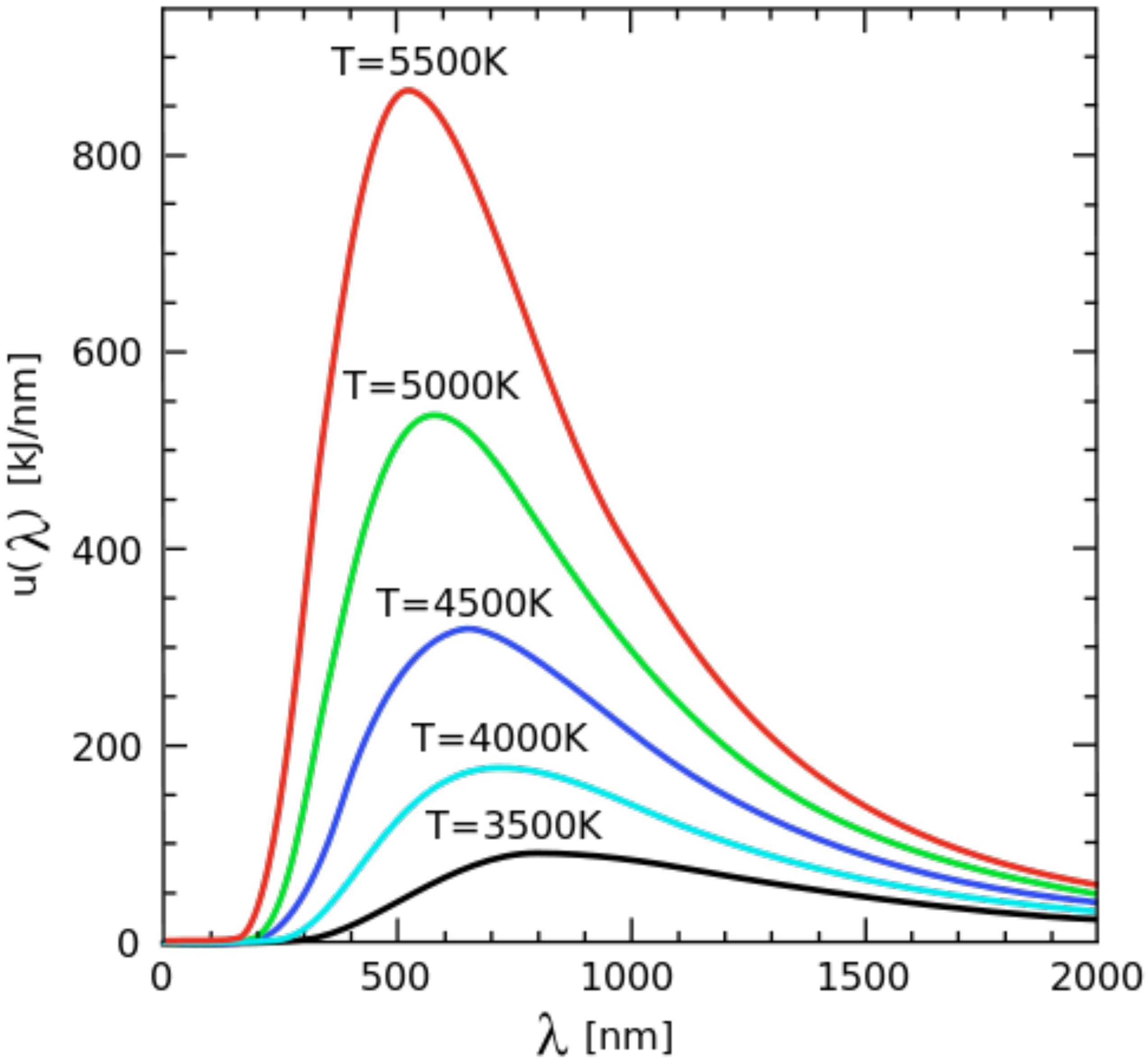


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} (PbPb) = 147 μb^{-1}
ρ, ω
φ
J/ψ
ψ(2S)
ϒ(1,2,3S)
Z
p_T^{μ} > 4 GeV/c
Events/(GeV/c²)
$m_{\mu\mu}$ (GeV/c²)

Thermal Radiation

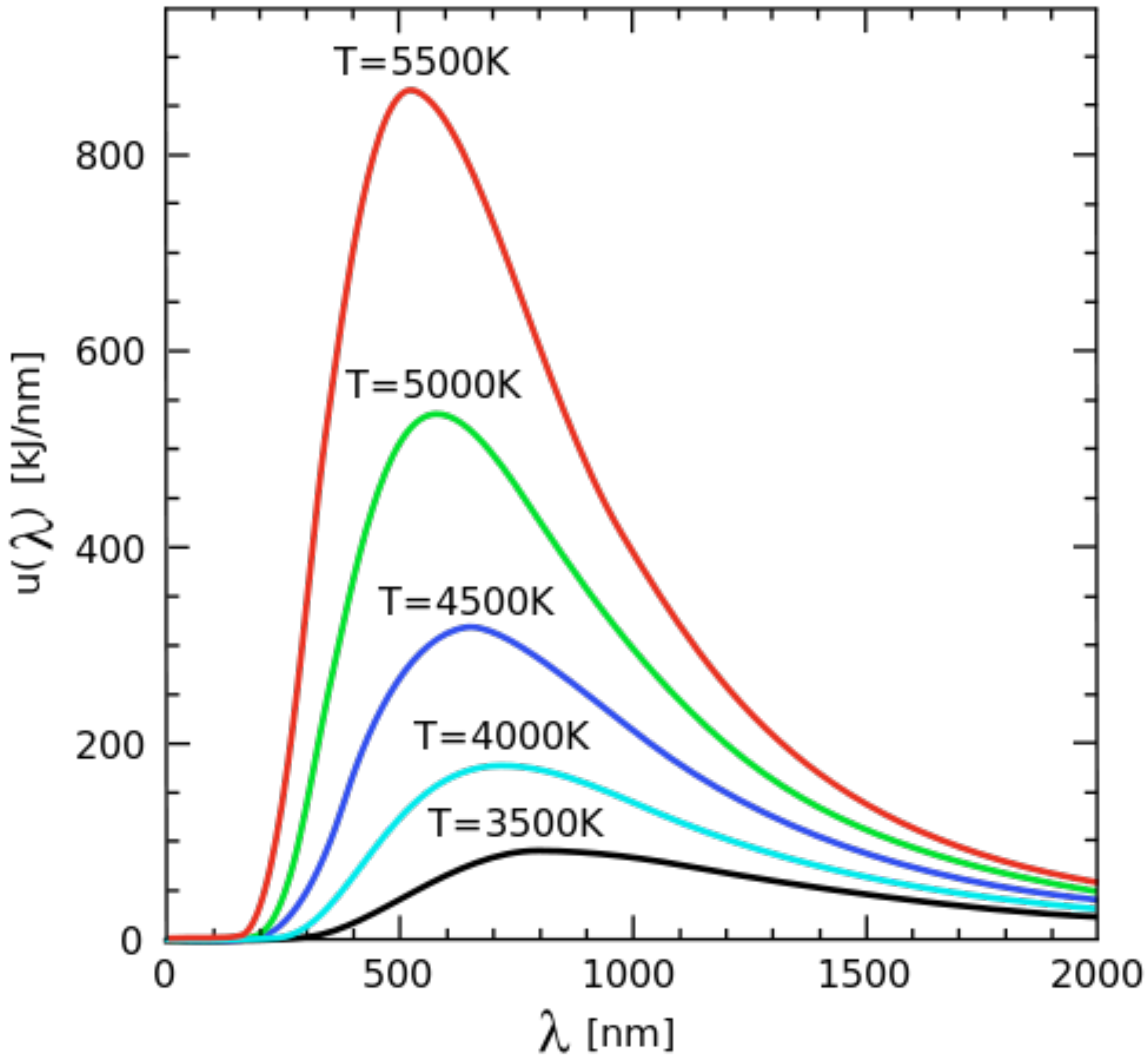


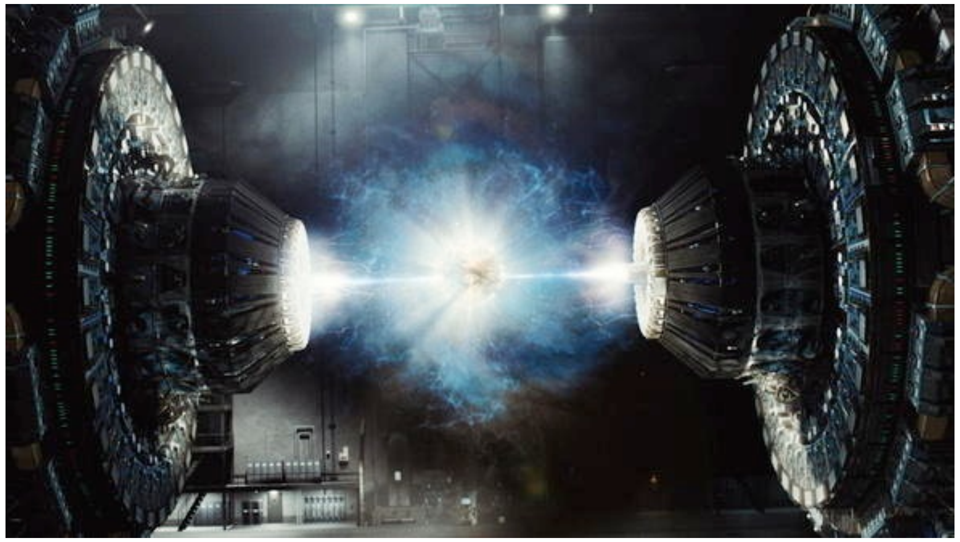
Thermal Radiation



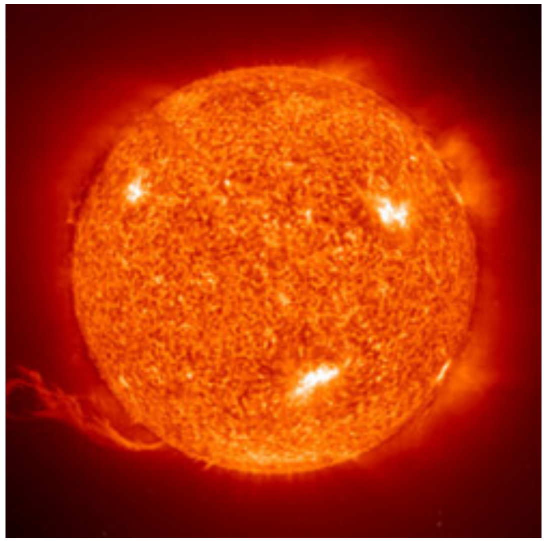
My Car

Thermal Radiation



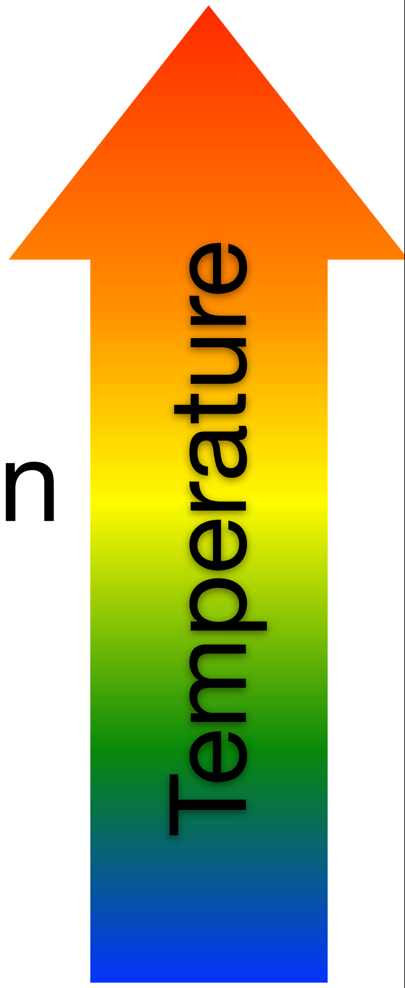


QGP

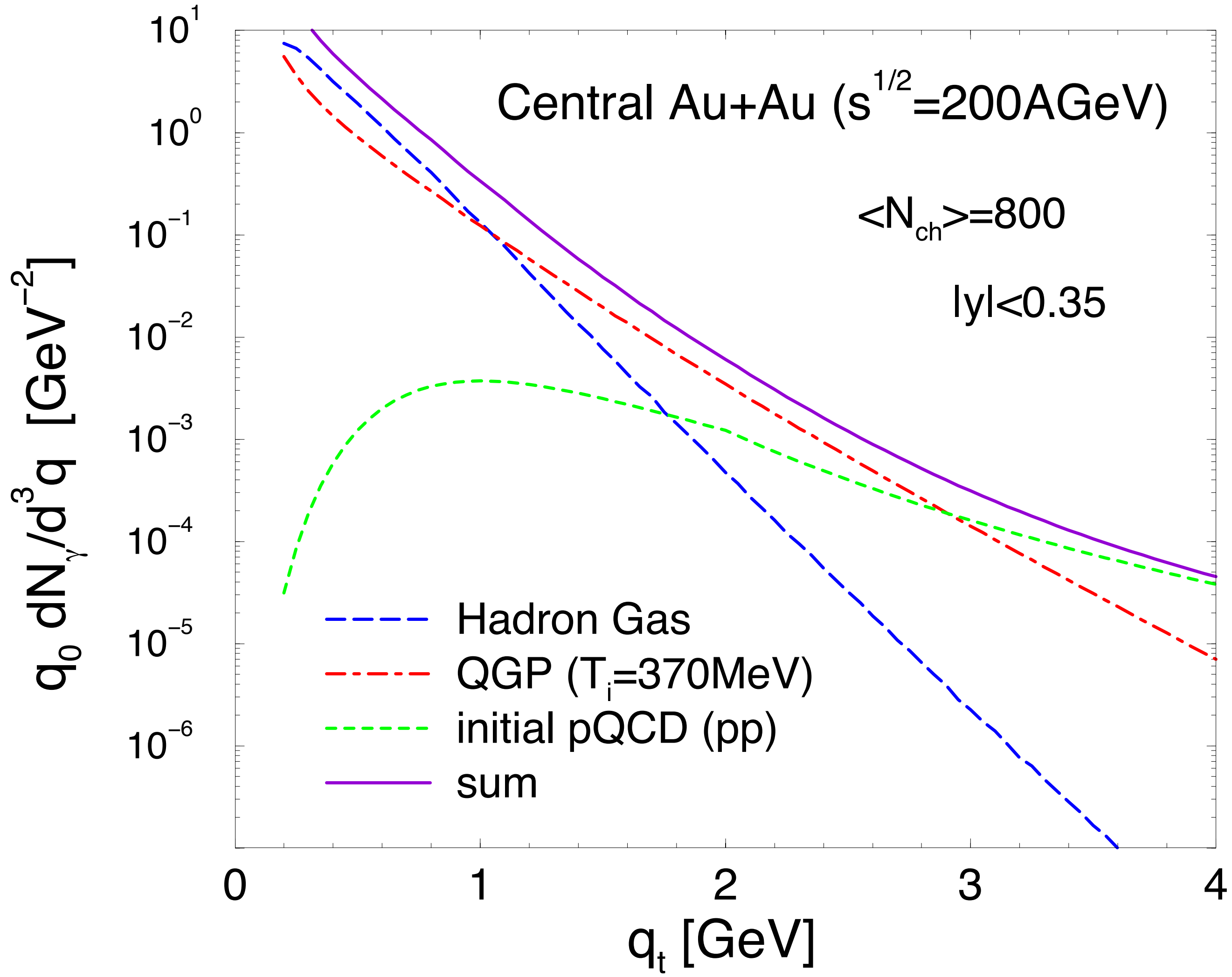


Sun

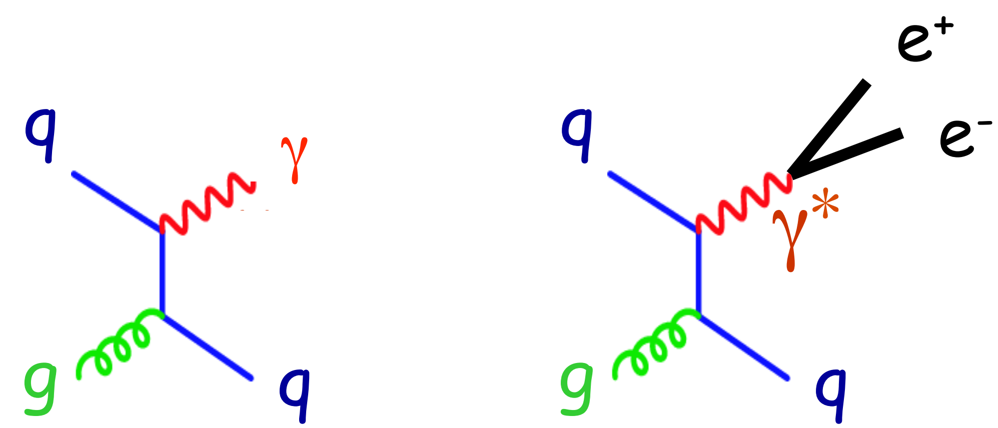
My Car



Thermal Radiation



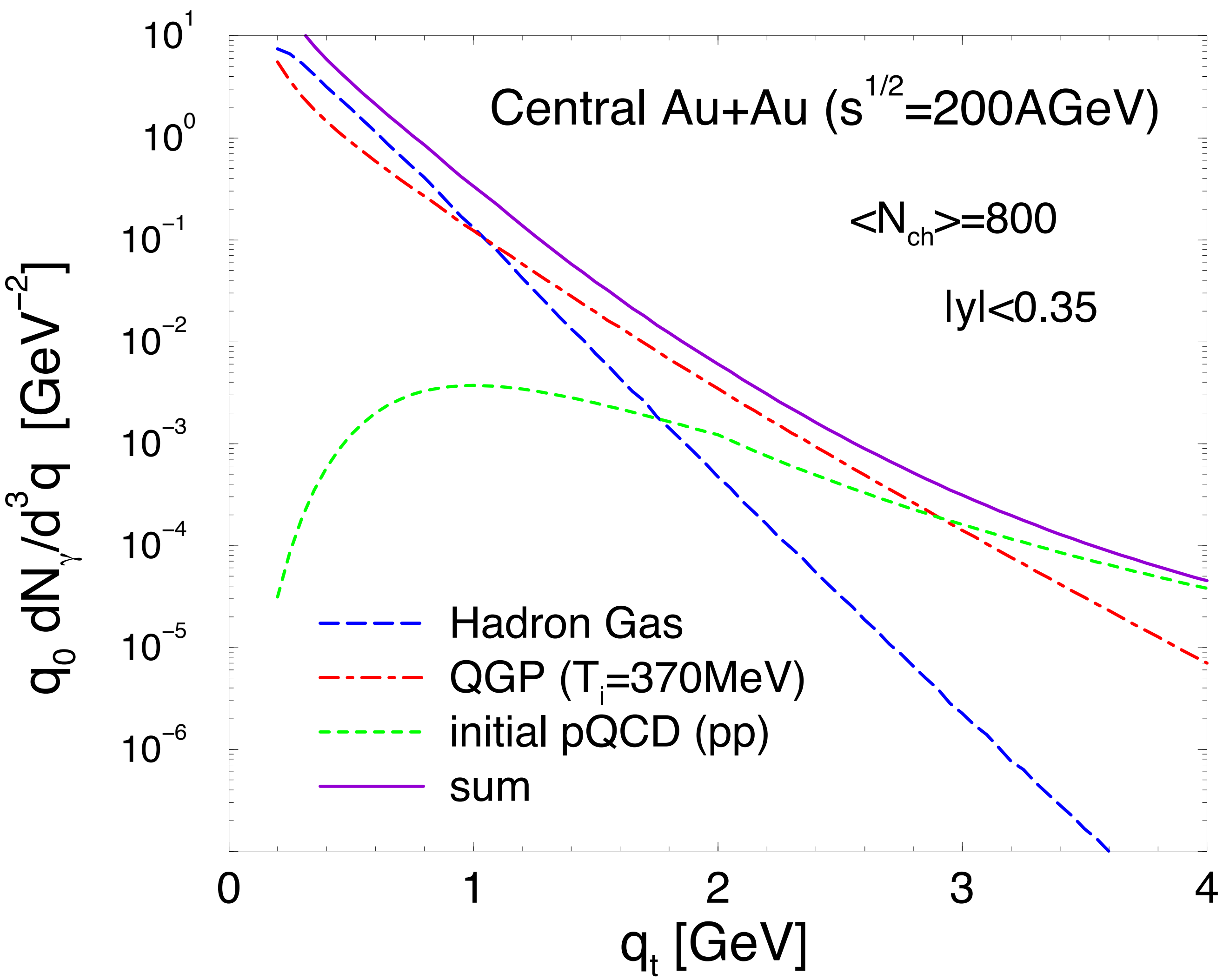
- Measure the energy spectrum of photons
  - real or virtual photons
  - Thermal photons in a QGP



  - Thermal photons in a Hadron Gas: e.g. $\pi + \rho \rightarrow \pi + \gamma$

- Need to subtract background sources
  - hadron decays
  - prompt photons from the initial parton-parton collisions

Thermal Radiation



- Measure the energy spectrum of photons
  - real or virtual photons
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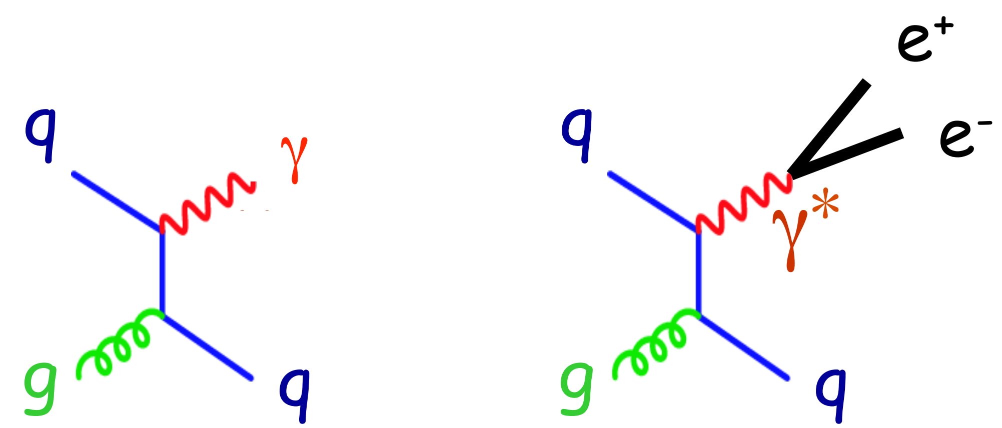


  - Thermal photons in a Hadron Gas: e.g. $\pi + \rho \rightarrow \pi + \gamma$

- No strong final state interaction
  - Leave reaction volume undisturbed and reach detector
- Emitted at all stages of the space time development
  - Information must be deconvoluted

- Need to subtract background sources
  - hadron decays
  - prompt photons from the initial parton-parton collisions

Dileptons vs. virtual photons

- Emission rate of thermal dileptons:

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

- Emission rate of thermal virtual photons

$$q_0\frac{dR_{\gamma^*}}{d^4q} = -\frac{\alpha}{2\pi^2}\mathrm{Im}\Pi^{\mu}_{\mathrm{em},\mu}(M,q;T)f^B(q_0,T)$$

- Relationship between them

virtual photon

$$q_0\frac{dR_{ll}}{dM^2d^3q} = \frac{1}{2}\frac{dR_{ll}}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}q_0\frac{dR_{\gamma^*}}{d^3q}$$

dileptons

prob. $\gamma^* \rightarrow l^+l^-$

- Virtual photon rate can be determined from measured dilepton rate

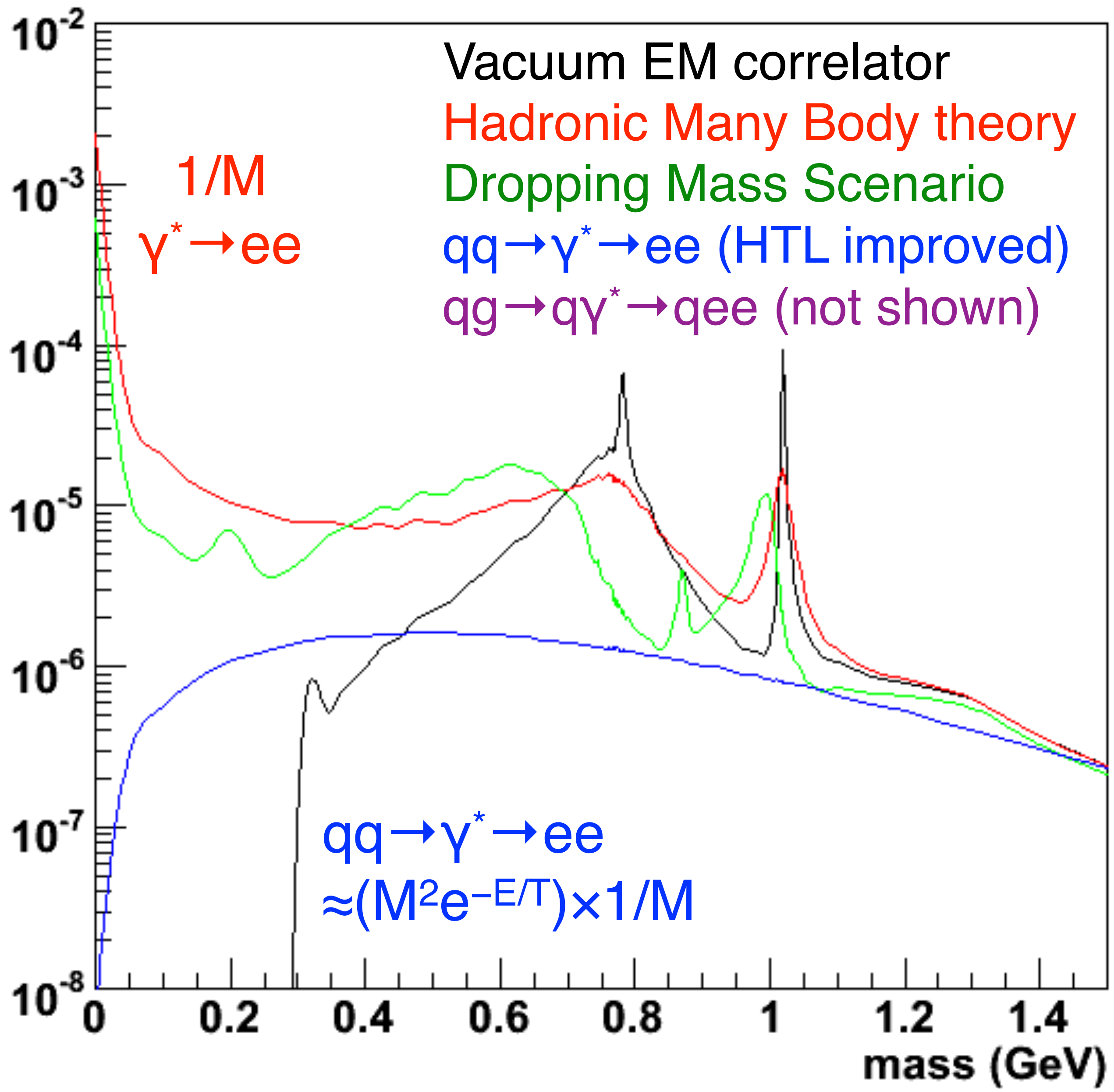
$$q_0\frac{dN_{\gamma^*}}{d^3q} = \frac{3\pi}{2\alpha}Mq_0\frac{dN_{ll}}{d^3q\,dM}$$

$M \times dN_{ll}/dM$ gives virtual photon yield

- Real photon rate $n_\gamma \leftarrow n_{\gamma^*}$ for $M \rightarrow 0$

Theory Prediction of Dilepton Emission

$$\frac{1}{p_T}\frac{dN_{ee}}{dp_T dy dM} \text{ at } y = 0 \text{ and } p_T = 1.025\,\mathrm{GeV}/c$$



- Usually the dilepton emission is measured and compared as $dN/dp_T dM$
- The mass spectrum at low p_T is distorted by the virtual photon→e^+e^- decay factor 1/M, which causes a steep rise near M=0
- q q annihilation contribution is negligible in the low mass region due to the M^2 factor of the EM correlator
- In the calculation, partonic photon emission process q g→q γ^*→q e^+e^- is not included

Theory calculation by R. Rapp