NA60+: hard and electromagnetic probes in a beam energy scan (BES) at the CERN SPS in the interval √s≈6-17 GeV

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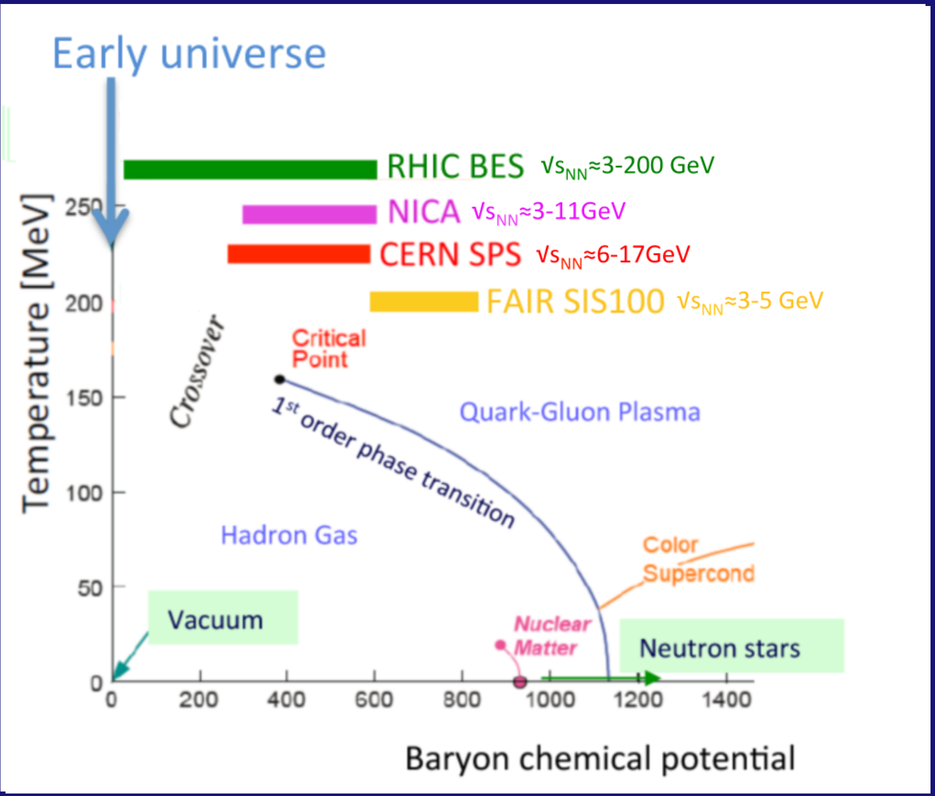
On behalf of the NA60+ working group - Cagliari (INFN), Kolkata (Saha institute), Lyon (IPNL), Munich (TUM), Padova (INFN), Rice University, Stony Brook University, Tohoku University (Japan), Torino (INFN)

ECT* Trento
30/11/2018

The low energy frontier: the QCD phase diagram at high baryon potential μ_B



- Largely unexplored:
  - Existence of critical point and first order phase transition put forward
- First order phase transition:
  - Measurement would provide first direct evidence (in thermodynamic sense) of a phase transition to the QGP
- Additional chiral phase transition:
  - Exploration of changes in the hadron spectrum

NA60+: hard and electromagnetic probes in a beam energy scan (BES) at the CERN SPS in the interval $\sqrt{s} \approx 6$-17 GeV

Physics goals

- First order phase transition with thermal dimuons:
  - caloric curve T vs energy density
- Chiral symmetry restoration with thermal dimuons:
  - ρ-a_1 chiral mixing
- Probe high μ_B medium with heavy flavors:
  - Dissociation of ground (J/ψ) and excited charmonium states ($\psi(2S)$, χ_c)
  - Charm hadro-chemistry and in-medium modifications

NA60+: hard and electromagnetic probes in a beam energy scan (BES) at the CERN SPS in the interval $\sqrt{s}\approx$6-17 GeV

Experimental observables

- Comprehensive measurement of full dilepton spectrum:
  - Thermal dimuons from threshold up to 3 GeV
  - Charmonium: J/ψ, $\psi(2S)$, χ_c
- Hadronic measurements:
  - Charmed mesons and baryons (D^0,$D^{\pm}$, D_s, Λ_c)
  - Strangeness (additionally)

Requirements: statistics and beams

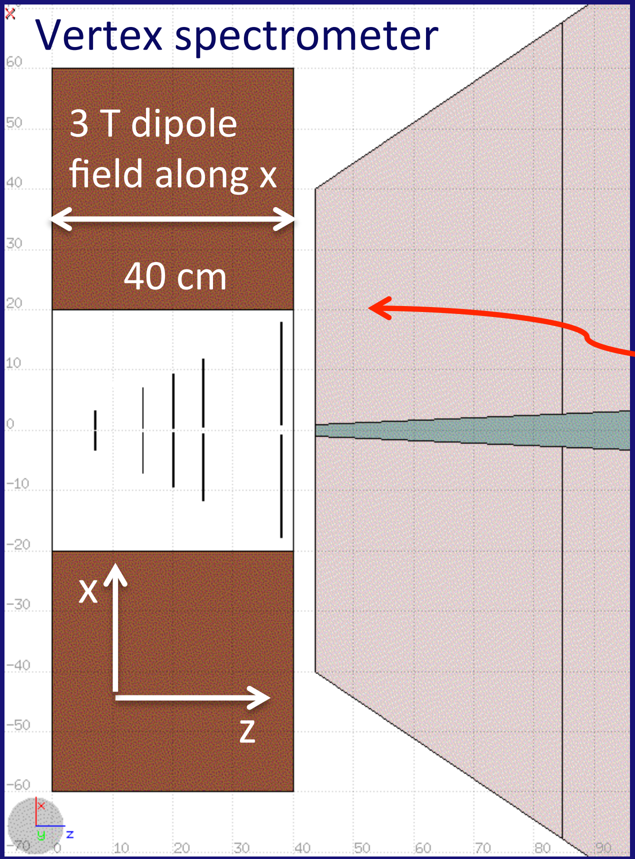
- Statistics goal at each energy of BES:
  - ~$5 \cdot 10^7$ reconstructed pairs from thermal dimuons (factor ≈100 over NA60)
  - ~$3 \cdot 10^4$ reconstructed J/ψ
  - ~10^7 reconstructed D^0

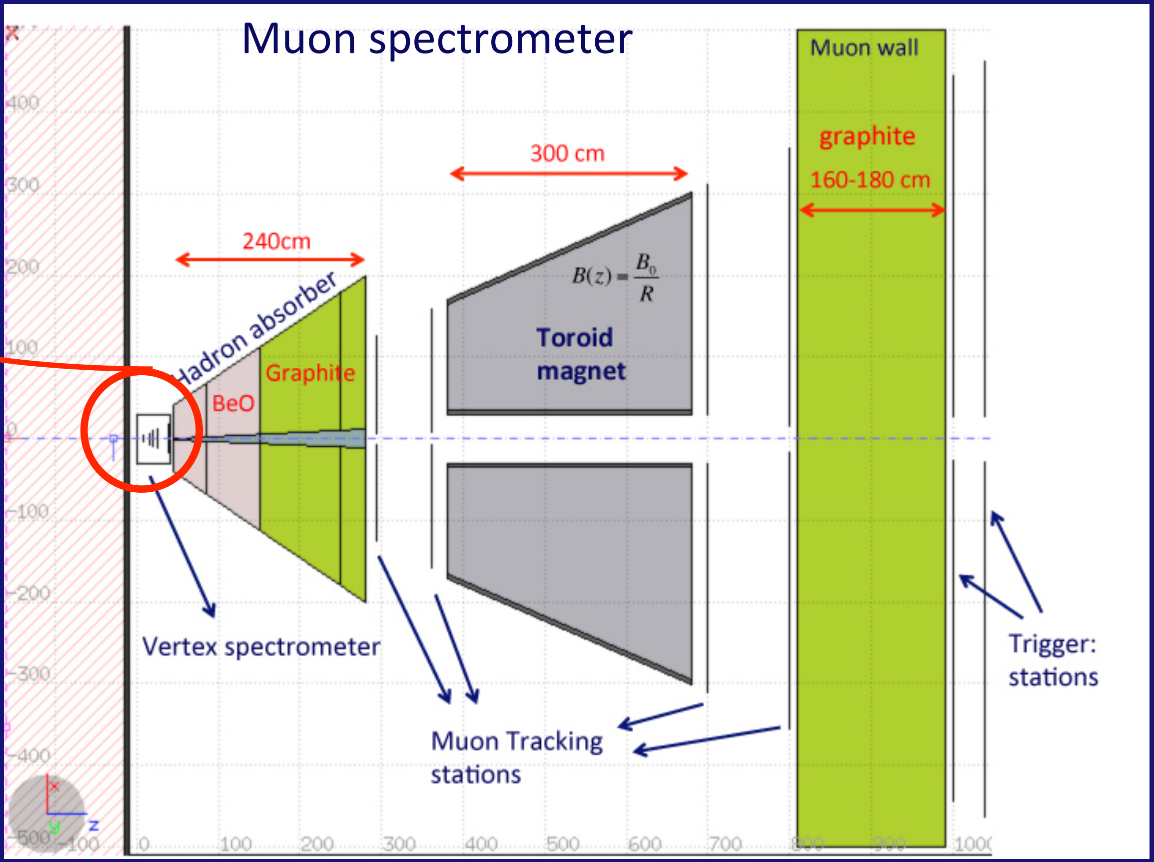
- The physics program of NA60+ includes, in terms of beams:
  - → ~4 week periods/year with Pb beams
    BES example (p_{lab}): 20, 30, 40, 80, 120, 160 GeV/nucleon
  - → corresponding periods of proton beams (reference),
    scan could be coarser

- To get the necessary integrated luminosity with 10% interaction probability, beam intensities of:
  - → ~10^7 ions/s are mandatory (assuming ~5 s bursts)
  - → ~5×10^8 p/s

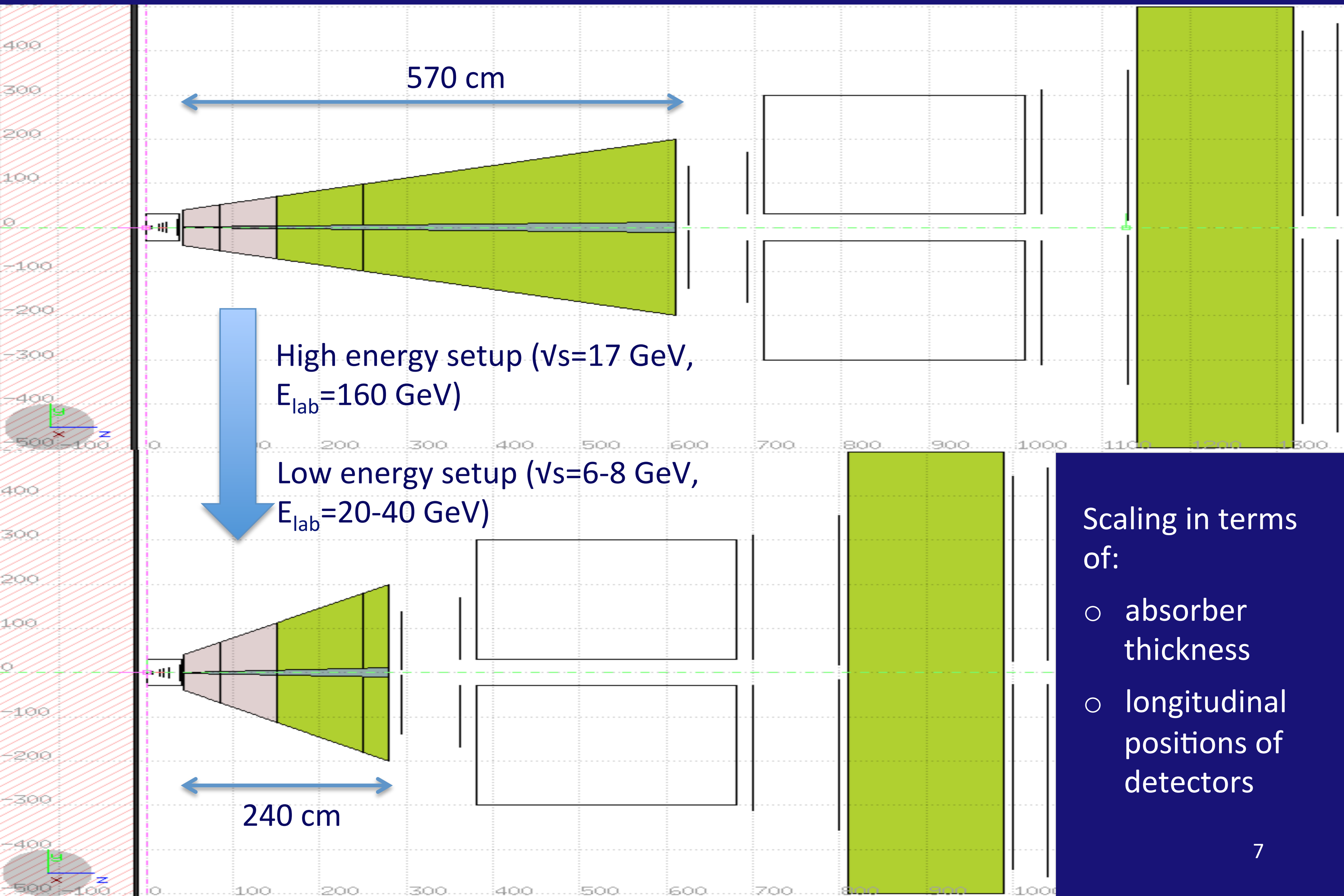
Experimental set-up

- NA60+ layout close to NA60:
  - precision muon measurement with tracking before and after hadron absorber





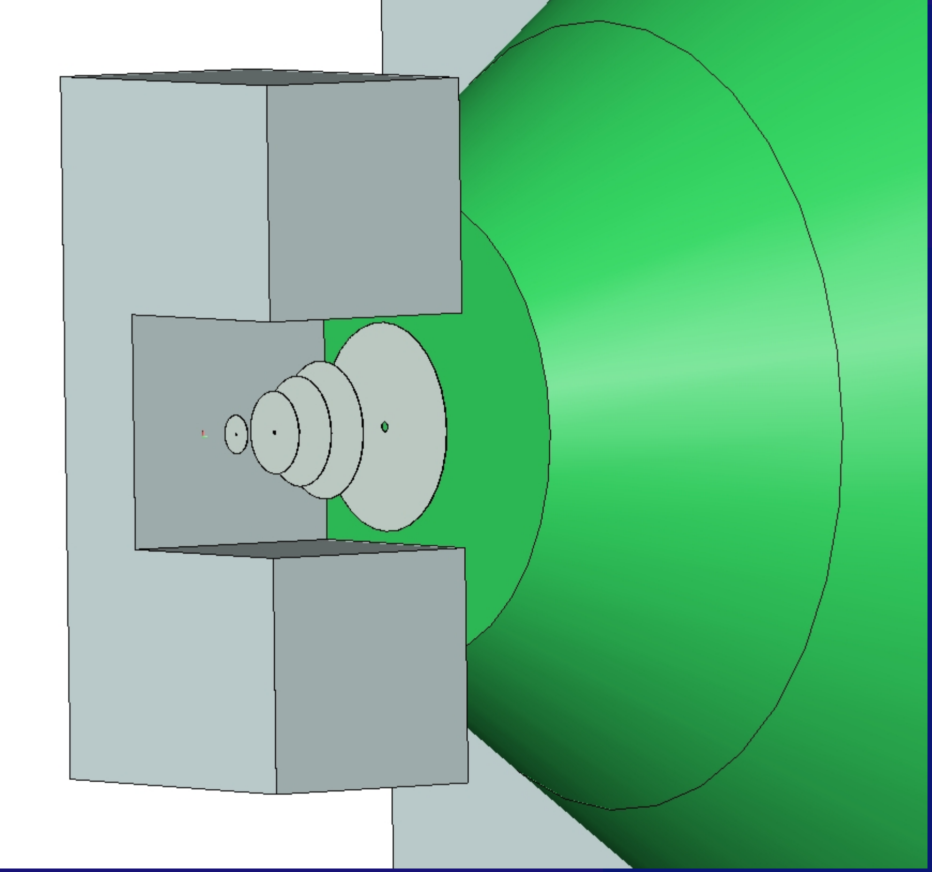
Scalable spectrometer for a BES

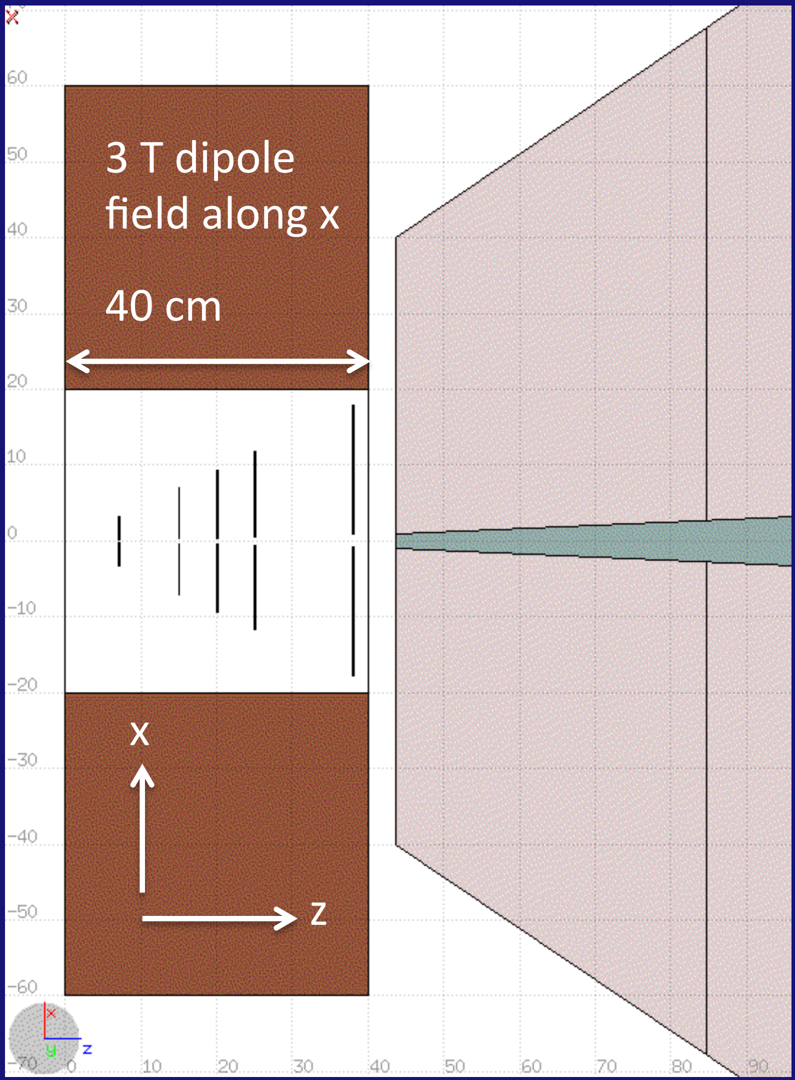


Scaling in terms of:

- absorber thickness
- longitudinal positions of detectors

The vertex spectrometer



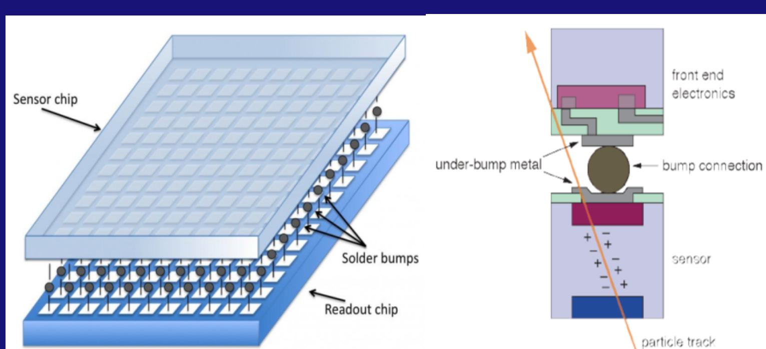


- angular coverage down to 1.6<η<4
- 5 silicon pixel stations at 7<z<40 cm
- Demading requirements from interaction rate of 1-2 MHz:
  - Particle flux ≈50 MHz/cm^2 in first station

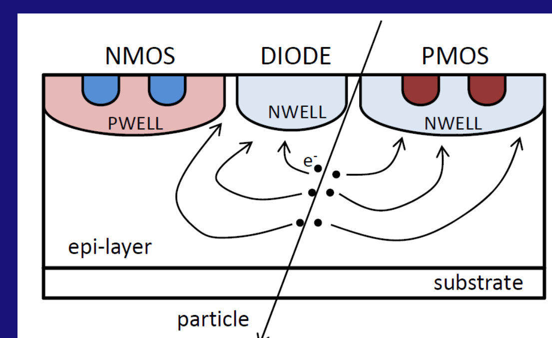
MAPS vs hybrid pixels

- sensor and frontend electronics in separate chips
- bump-bonding:
  - limits pixel size (pitch: 50 µm, thickness: >150 µm→ multiple scattering)
  - expensive
- charge collection by drift → Vbias 10 to 100 V
- high power consumption ~30mW/mm²
- radiation hard technology

- Sensor and frontend electronics in the same silicon wafer
- NO Bump-bonding:
  - (pixel pitch: 30 µm, thickness down to 50 µm)
- charge collection drift/diffusion→Vbias 0 a 10V
- low power consumption~ 3mW/mm²
- radiation toleratn technology
- more limited frontend electronics



CMS, ATLAS HL-LHC



ALICE

MAPS state of the art: ALICE ALPIDE

Pixel chip developed for the ITS Upgrade

Parameter	Inner Barrel	Outer Barrel	ALPIDE
Silicon thickness	50µm	100µm	✔
Spatial resolution	5µm	10µm	~ 5µm
Chip dimension	15mm x 30mm		✔
Power density	< 300mW/cm^2	< 100mW/cm^2	< 40mW/cm^2
Event-time resolution	< 30µs		~ 2µs
Detection efficiency	> 99%		✔
Fake-hit rate *	< 10^{-6}/event/pixel		<<< 10^{-6}/event/pixel
NIEL radiation tolerance **	1.7x10^{13} 1MeV n_{eq}/cm^2	10^{12} 1MeV n_{eq}/cm^2	✔
TID radiation tolerance **	2.7Mrad	100krad	tested at 350krad

* revised numbers w.r.t. TDR
** including a safety factor of 10, revised numbers w.r.t. TDR

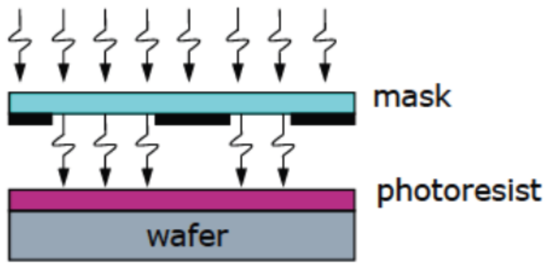
- Max particle rate ~ 100MHz /cm^2 (pile-up)
- Max readout rate ~ 10 MHz/cm^2 (bandwidth)

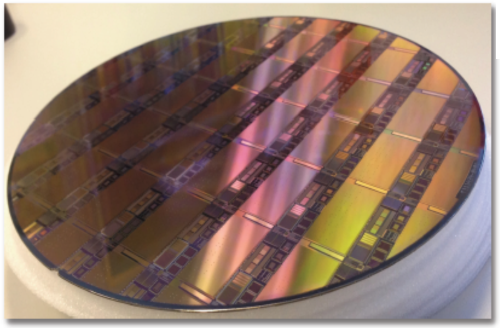
Large area sensors with stitching

CMOS photolithographic process defines wafer reticles size

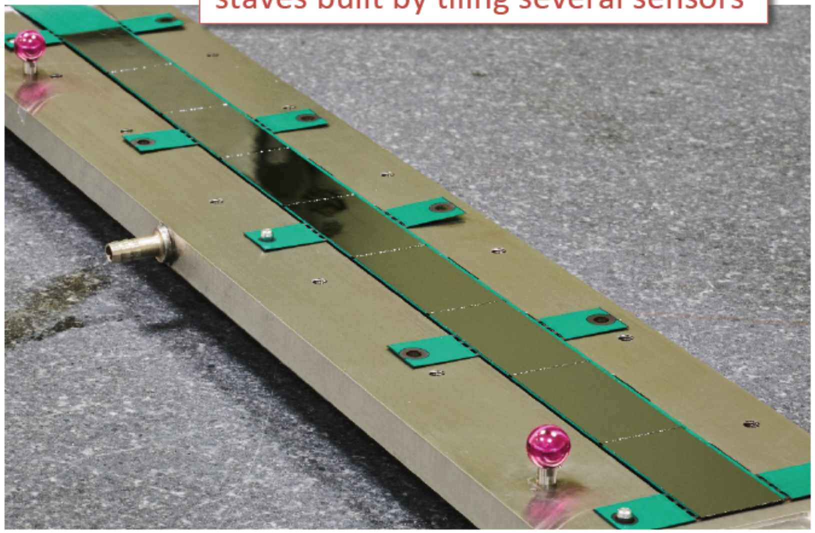
⇨ Typical field of view O(2 x 2 cm²)

Reticle is stepped across the wafers to create multiple identical images of the circuit(s)

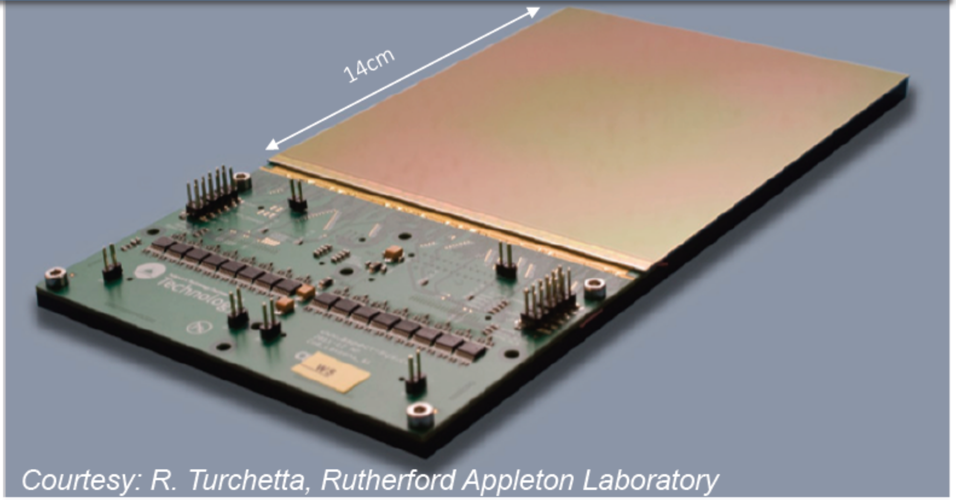




staves built by tiling several sensors



Stitching allows fabrication of sensors larger than the reticle size



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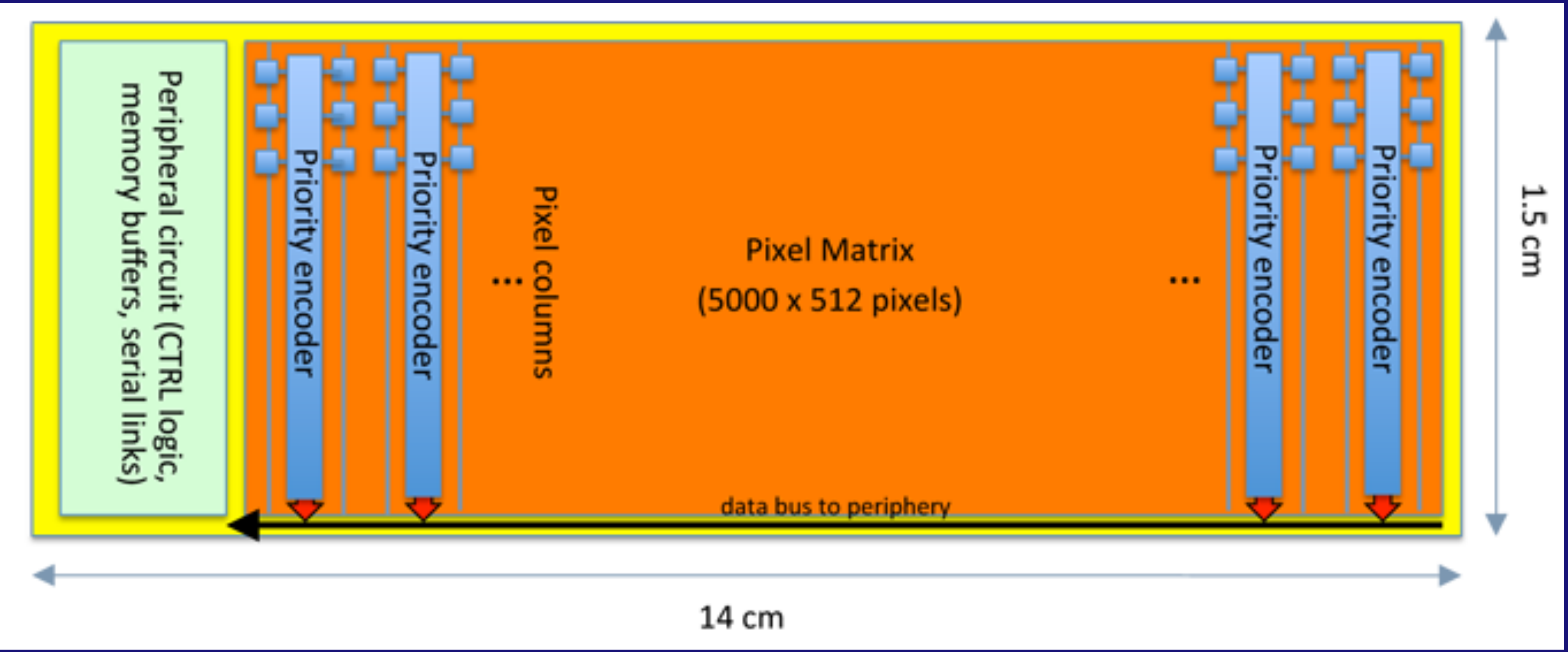
Stitching PALPIDE

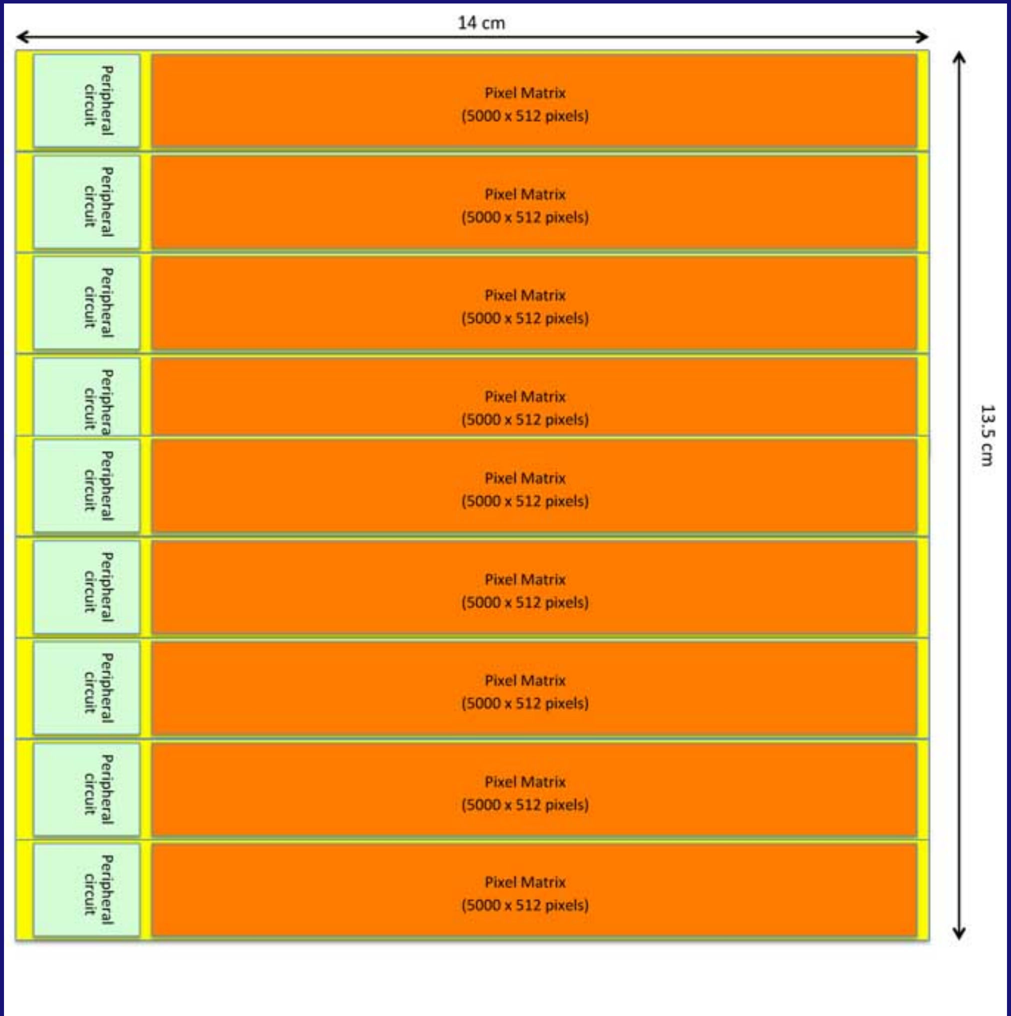


1.5x14 cm^2 sensor: same column length as in ALPIDE (PE readout)

data are transmitted from the bottom of the columns along one long side of the sensor to the periphery

periphery: contains the control logic to steer the priority encoders, the interfaces for the configuration of the chip and serial data transmitters

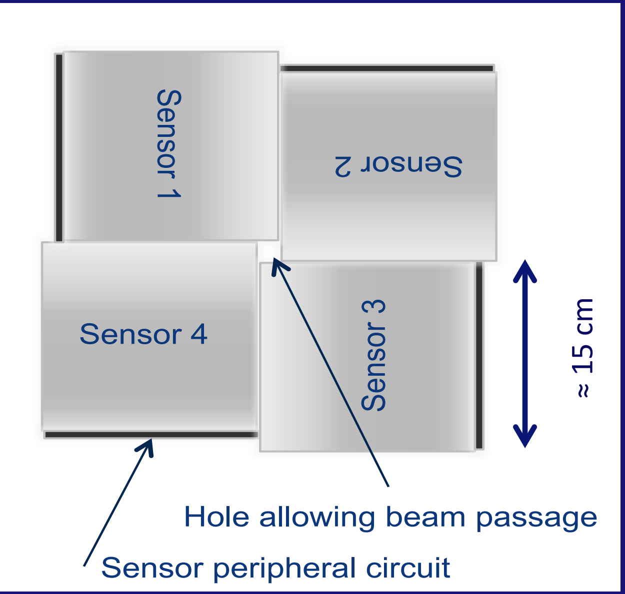
Massless silicon tracker with wafer scale sensors



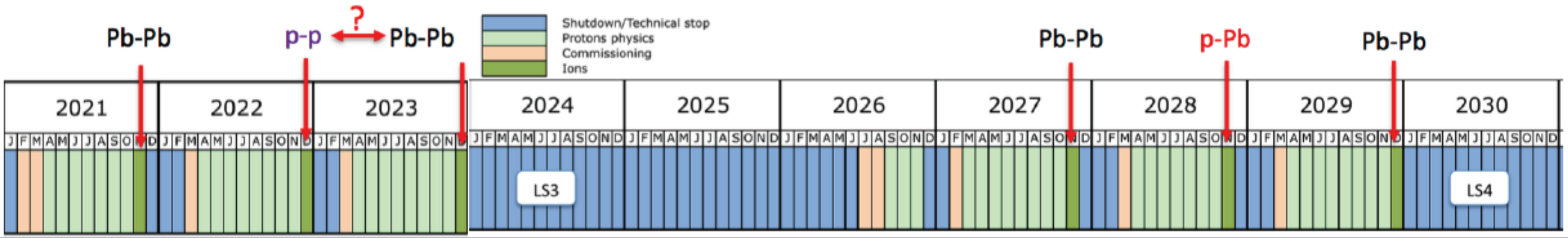
Wafer-scale sensor (5000 x 5000 pixels) obtained replicating this sensor chip several times along the periphery side

Mechanical support structures and colling only on the borders outside from acceptance

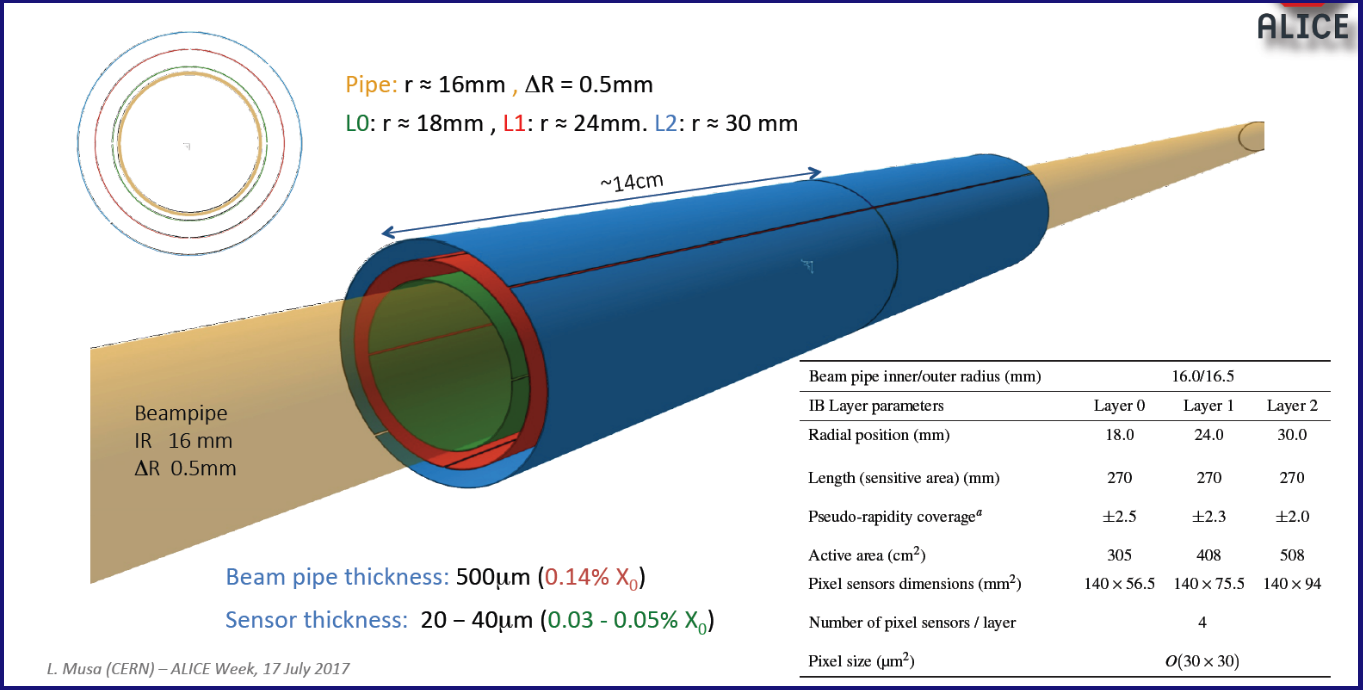
Material budget for tracking stations of about 0.005-0.1 % X_0



ALICE ITS super-upgrade after LS3



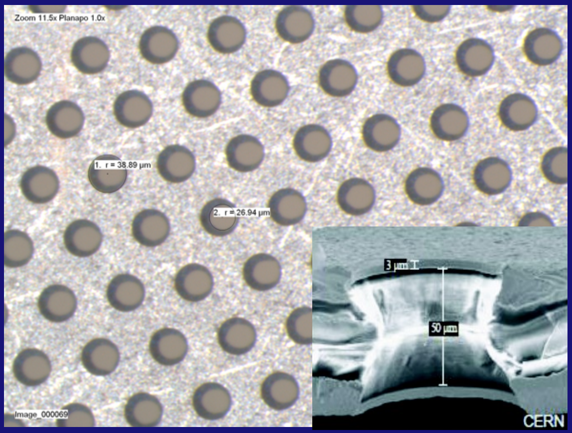
Expression of interest: Study of an almost "massless" ITS Inner Barrel based on the stiched sensors (upgrade foreseen during LS3)



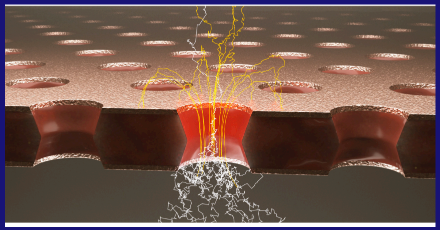
Beam pipe inner/outer radius (mm)		16.0/16.5	
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0	24.0	30.0
Length (sensitive area) (mm)	270	270	270
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	408	508
Pixel sensors dimensions (mm^2)	140 × 56.5	140 × 75.5	140 × 94
Number of pixel sensors / layer		4	
Pixel size (μm^2)		$O(30 \times 30)$	

GEM (Gas Electron Multiplier)

GEM foil



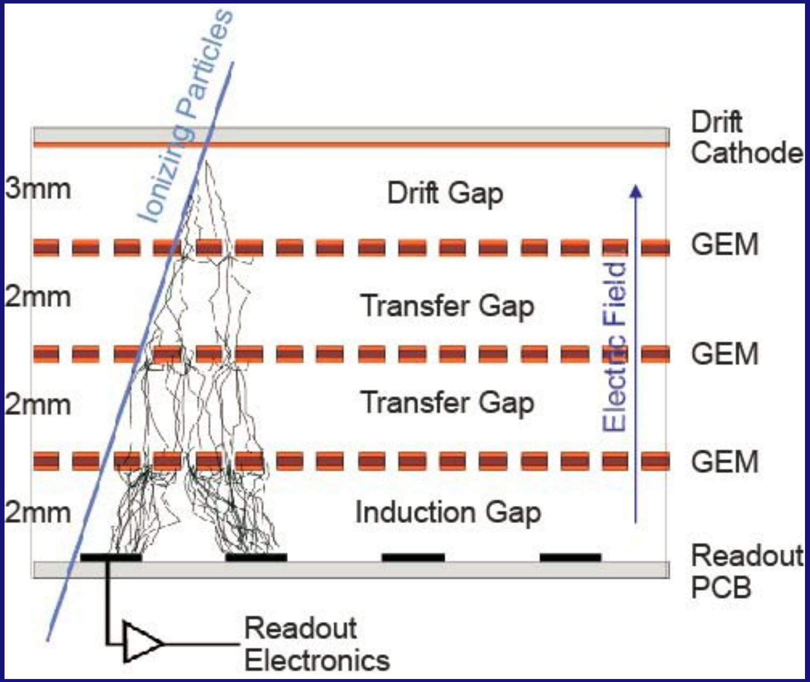
- Thin polyimide foil (Kapton®) ~50 µm
- Cu-clad on both sides ~5 µm
- Photolithography: ~10^4 holes/cm^2



Typical GEM geometry:

- Inner/Outer hole diameter: 50/70 µm
- **Pitch**: 140 µm

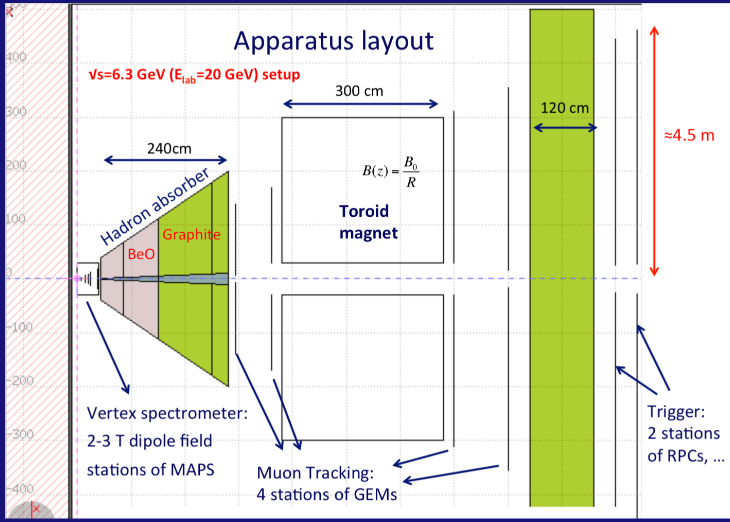
Triple GEM stack

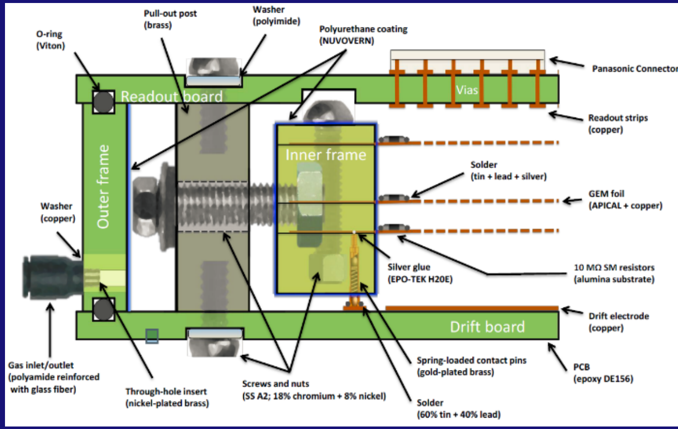


- Position resolution < 100 µm
- Timing resolution < 10 ns
- High rate capabilities of $\mathcal{O}$(1 MHz/cm^2)
- Radiation hardness
- Can be stacked easily:
  - Higher gains (up to 10^5)
  - Improved stability against electrical discharges
  - Further reduction of ion backflow
- Used successfully in COMPASS, LHCb, TOTEM
- Baseline solution for CMS Muon Endcap Upgrade, ALICE TPC Upgrade

NA60+ GEM tracker

- 4 stations, behind the absorber, total area of 116 m^2
- Double 3-GEM modules with strip readout per station
- Single module: 50 × 100 cm^2 - 50 × 150 cm^2
- 310 - 464 chambers → 1000 - 1500 GEMs (with spares)
- NS2 system (like CMS) for faster chamber assembly (no gluing)
- Gas: $Ar\text{-}CO_2$ or $Ar\text{-}CO_2\text{-}CF_4$
  - No flammable
  - No ageing effects observed





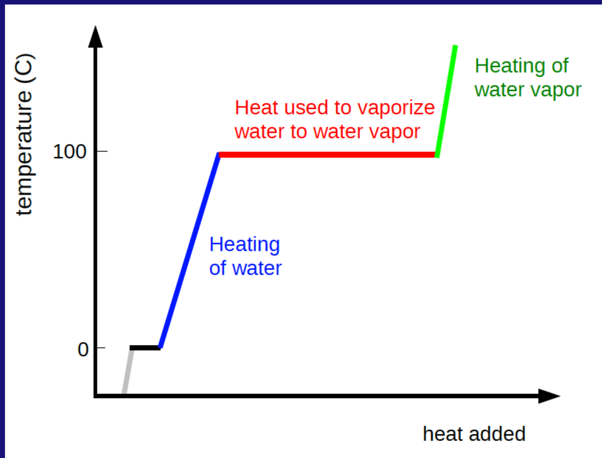
- 1-2 M electronic channels (1D or 2D). Readout options: VFAT-3, VMM-3 chips
- Significant effort necessitates in a collaboration of several production institutes and highly optimized workflow

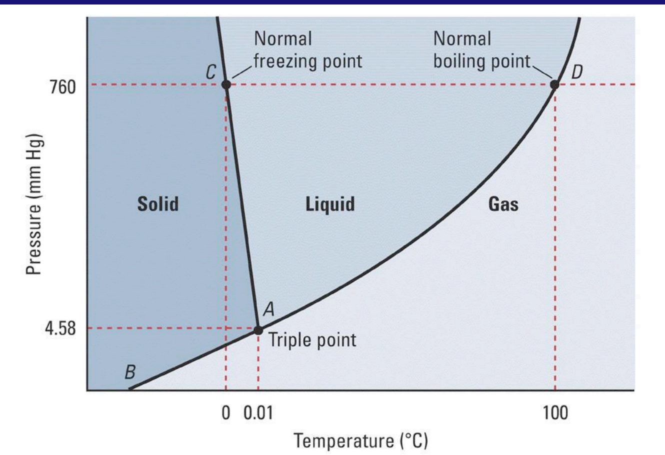
- Production time: 2-3 years
- Total cost: $\mathcal{O}$(10 MCHF)

Thermal radiation

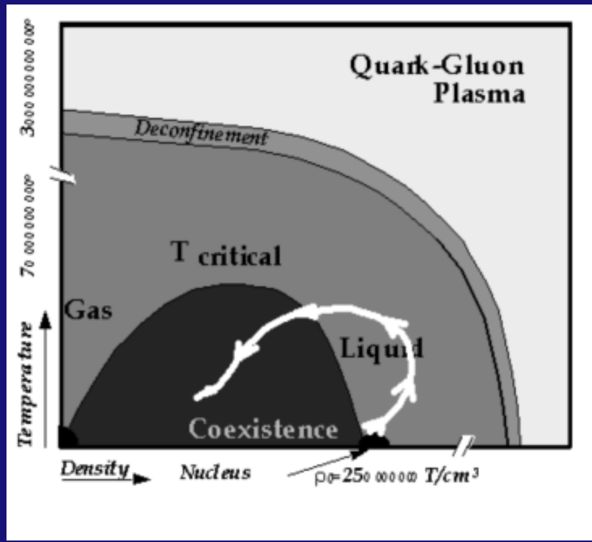
Phase transitions and caloric curves

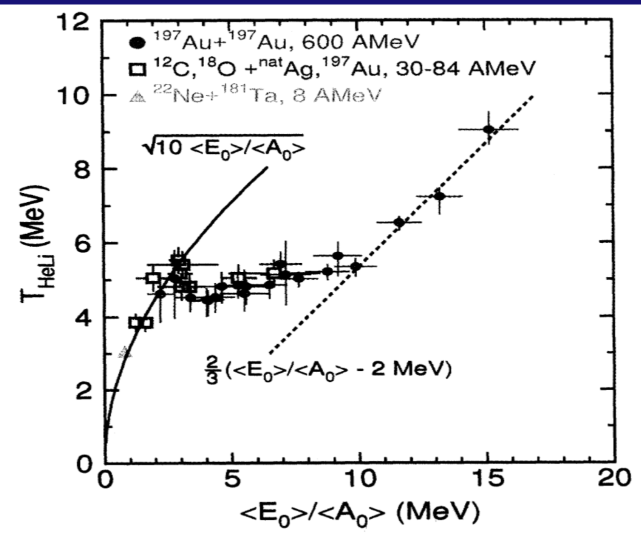
- Caloric curve and phase diagram of water



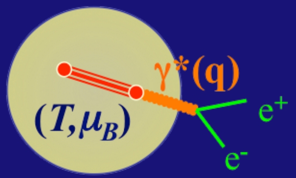


- Caloric curve for liquid-hadron gas phase transition in nuclear matter (Pochodzalla et al., Phys. Rev. Lett. 75 (1995), D'Agostonio et al., Nucl. Phys. A749 (2005) 55–64)



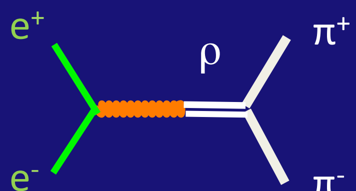


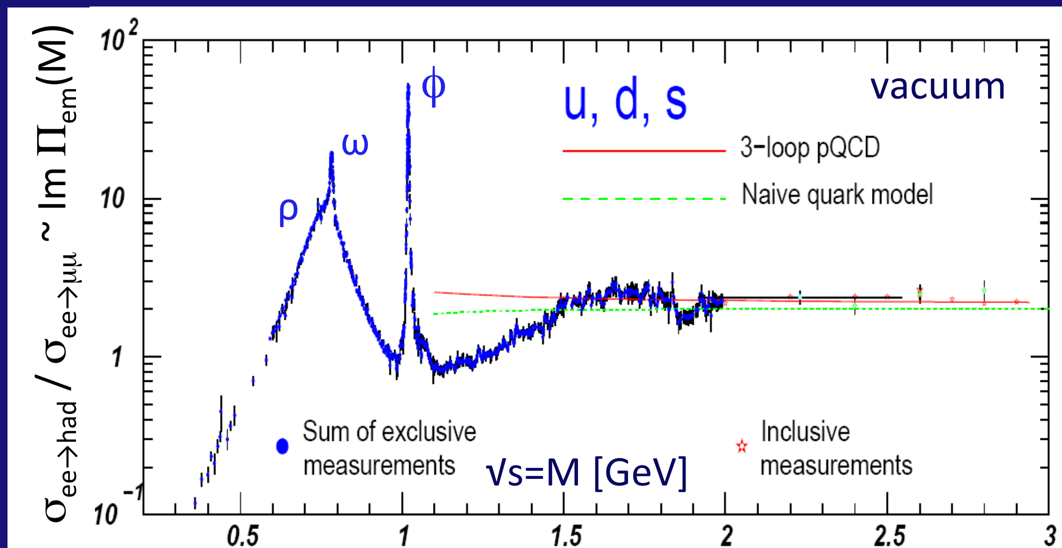
Thermal dilepton rate and the measurement of T

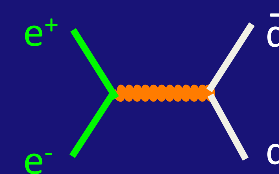


$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T) \times \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

e.m. spectral function







non-perturbative
in-medium
spectral function(s)

$\mathrm{Im}\Pi_{em} \sim \mathrm{Im}\, D_\rho + \ldots$

perturbative
hadron-parton
duality (flat SF)

$\mathrm{Im}\,\Pi_{em} \sim N_c \sum (e_q)^2$

Flat spectral function for M>1.5 GeV → mass spectrum after integration over momenta and emission 4-volume:

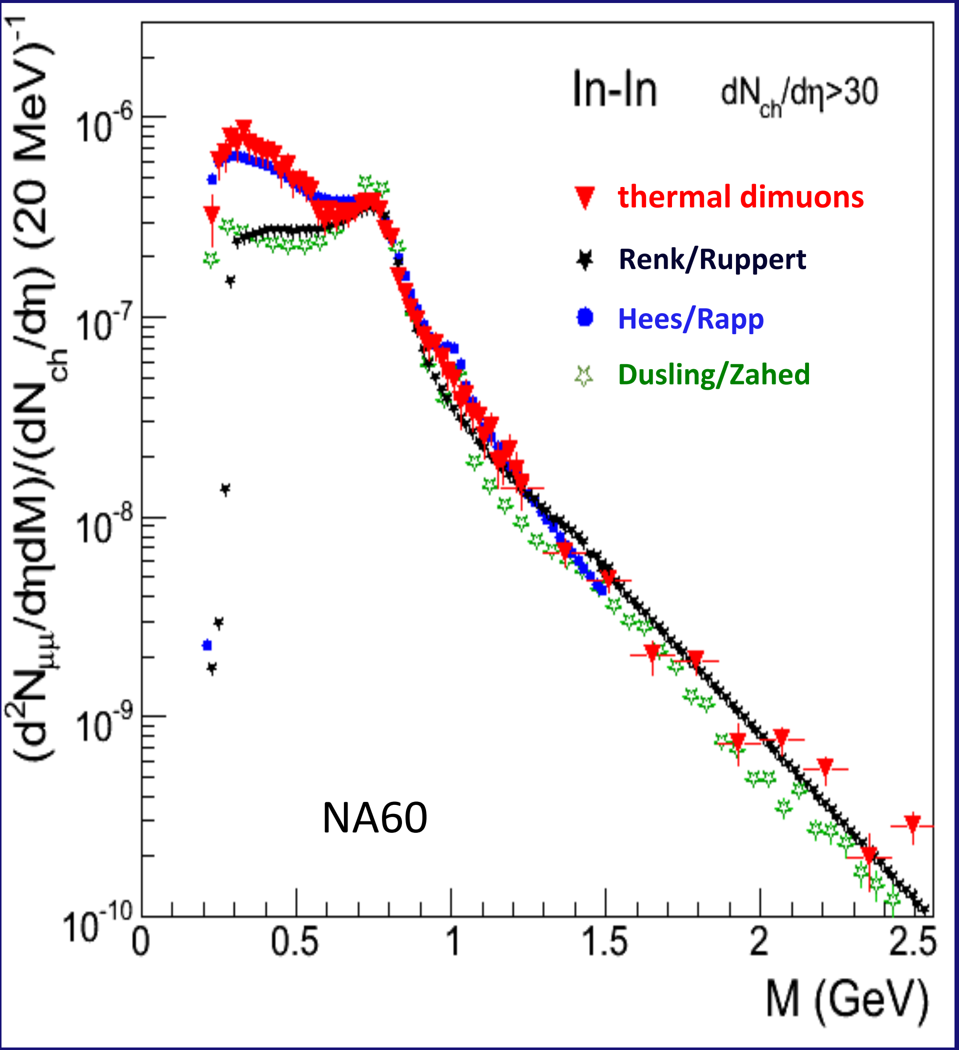
$$dN_{\mu\mu}/dM \propto M^{3/2} \times \langle \exp(-M/T) \rangle$$

T: average temperature which tracks initial temperature (dominant contribution from early stages)
Robust theoretical result

Fit of mass spectrum for M>1.5 GeV → thermometer!

NA60 measurement of T at √s=17.3 GeV (E_{lab}=160 GeV): evidence of deconfinement

[Eur. Phys. J. C 59 (2009) 607] → CERN Courier 11/ 2009, 31
Chiral 2010 , AIP Conf.Proc. 1322 (2010) 1



All physics background sources subtr. and integrated over p_T

Correction for acceptance and normalization to $dN_{ch}/d\eta$

effective statistics highest of all experiments, past and present (by a factor of nearly 1000)

M<1 GeV

ρ dominates, 'melts' close to T_c

M>1 GeV

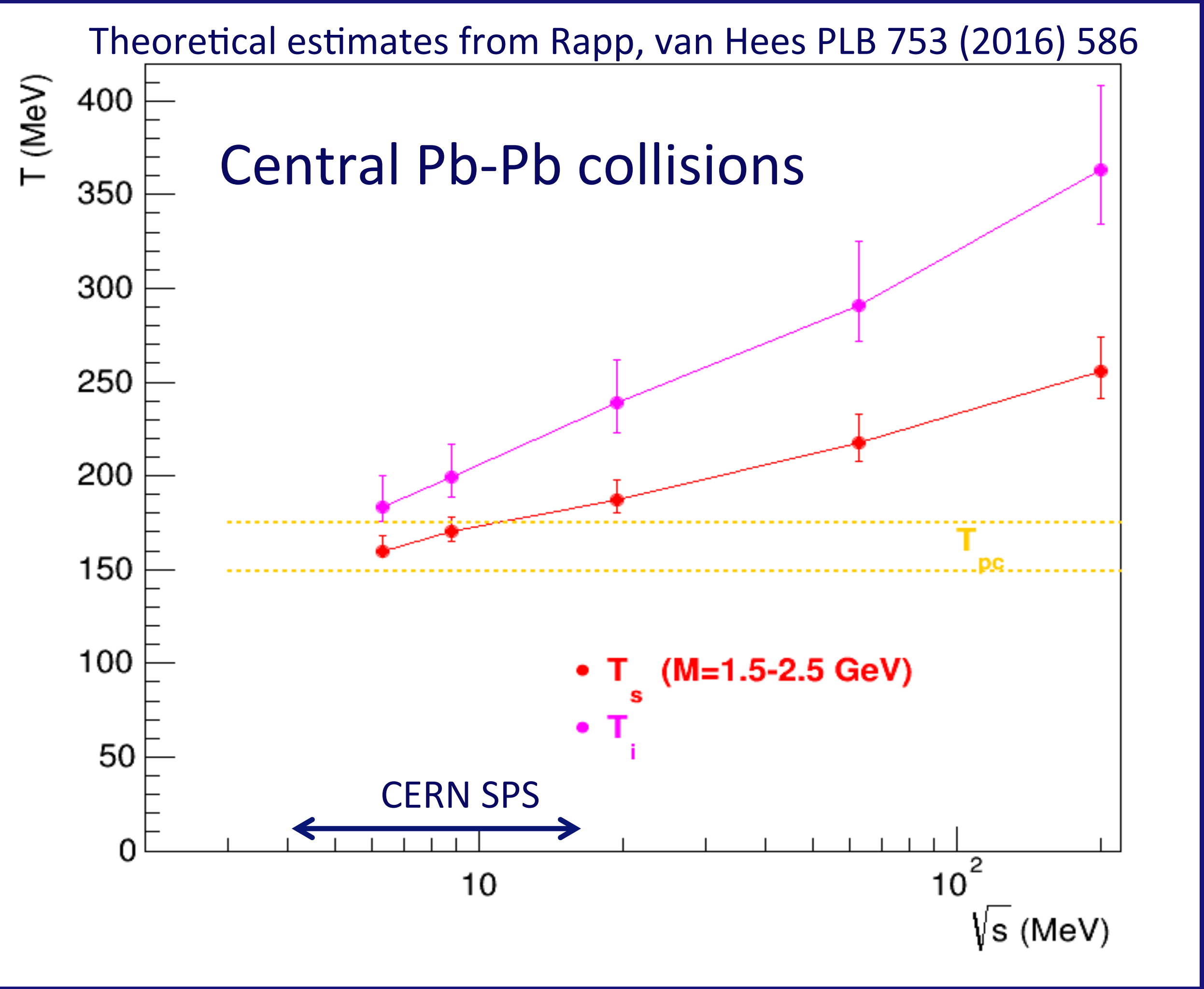
~ exponential fall-off → 'Planck-like'

fit to $dN/dM \propto M^{3/2} \times \exp(-M/T)$

range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV

$T>T_c$=160-170 MeV: partons dominate

Caloric curve: precision of the measurement

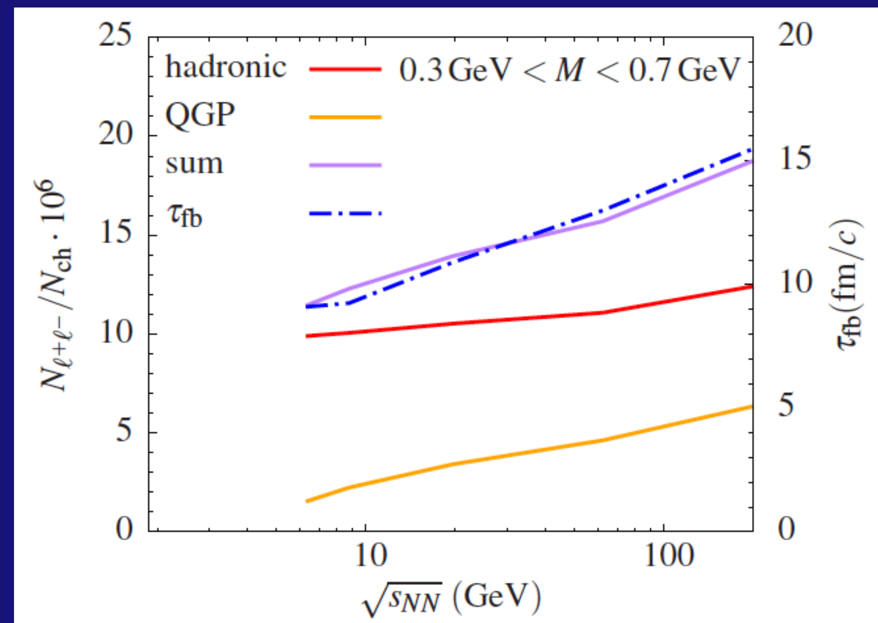


- First order hadron gas-QGP phase transition:
  - energy range below √s=10 GeV appears to be well suited to map out this transition regime (as suggested by this theoretical model)
- Experimental caloric curve with dilepton thermometer (T_s):
  - Fit of dilepton spectra for 1.5<M<2.5 GeV with
    $dN/dM \approx M^{3/2} exp(-M/T_s)$
- Identifying a flattening requires measuring T with very high precision

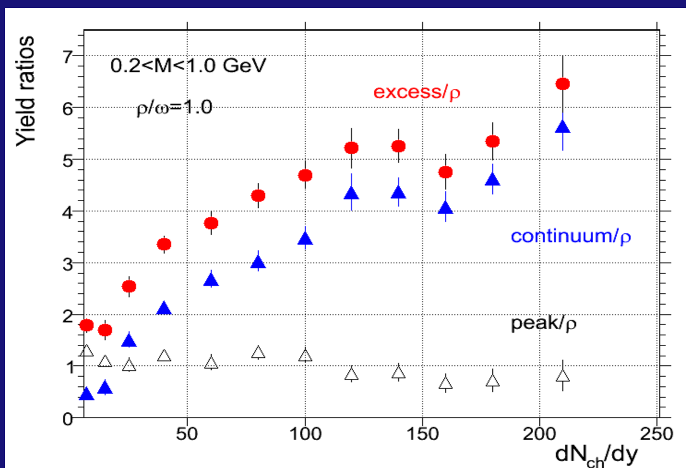
Thermal dilepton excitation function: fireball lifetime

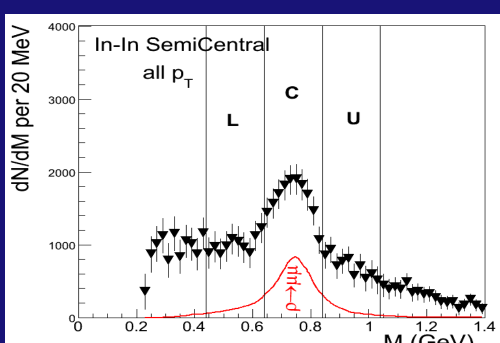
Precise thermal dilepton measurement of thermal yield in 0.3<M<0.7 GeV sensitive to the fireball lifetime

Hees, Rapp, Phys. Lett. B 753 (2016) 586



Eur. Phys. J. C61 (2009) 711





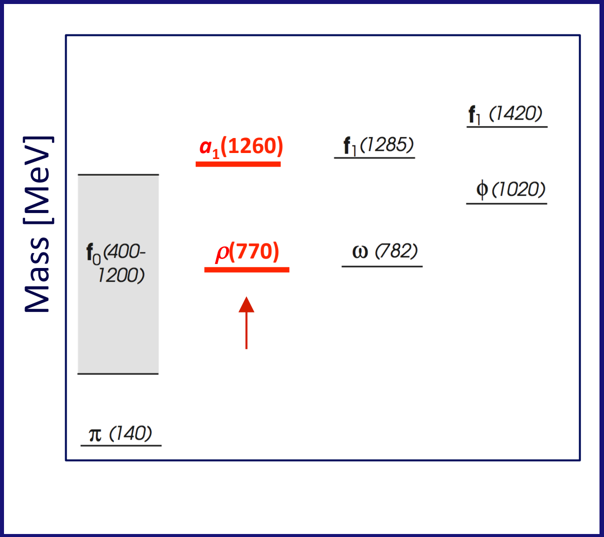
peak: R=C-1/2(L+U)
continuum: 3/2(L+U)

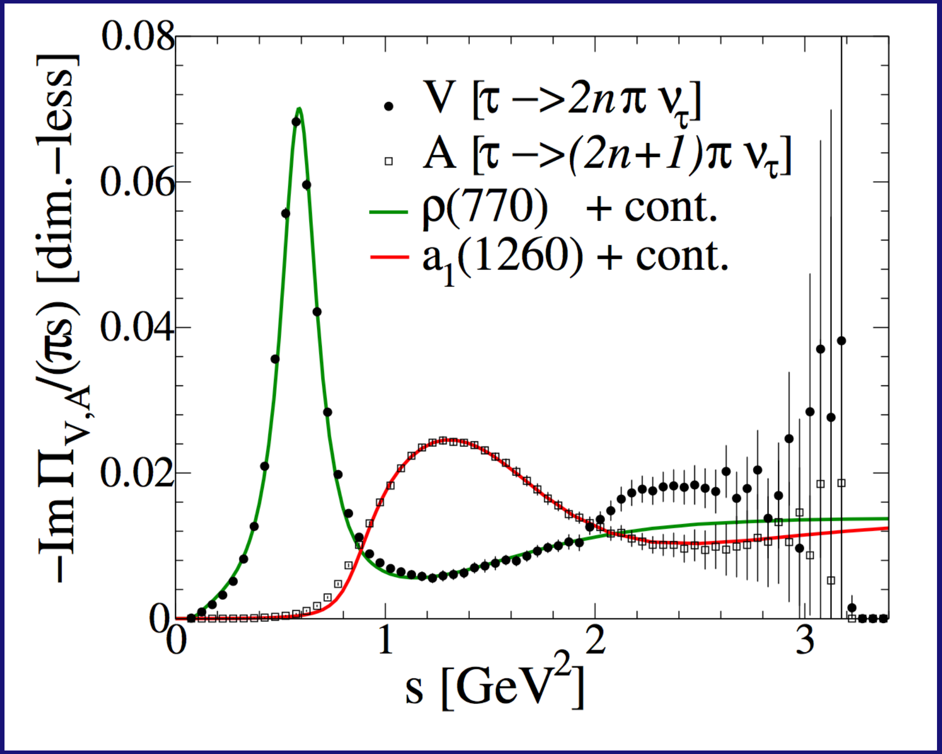
Low-mass dileptons:

- excellent tool to detect anomalous variations in the fireball lifetime due, for instance, to the presence of a soft mixed phase

Chiral symmetry breaking and the hadron spectrum

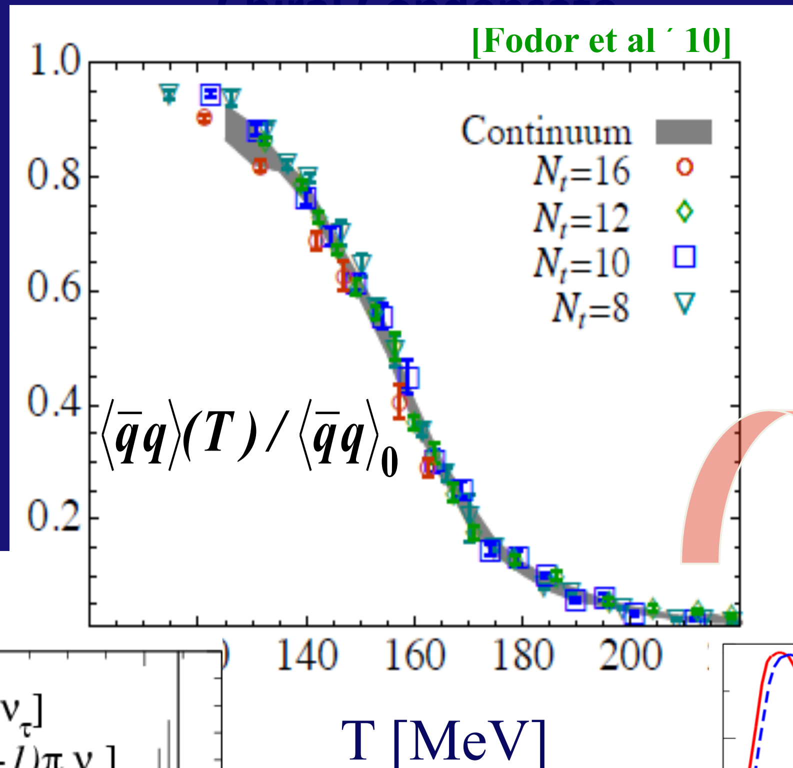
Hadron spectrum



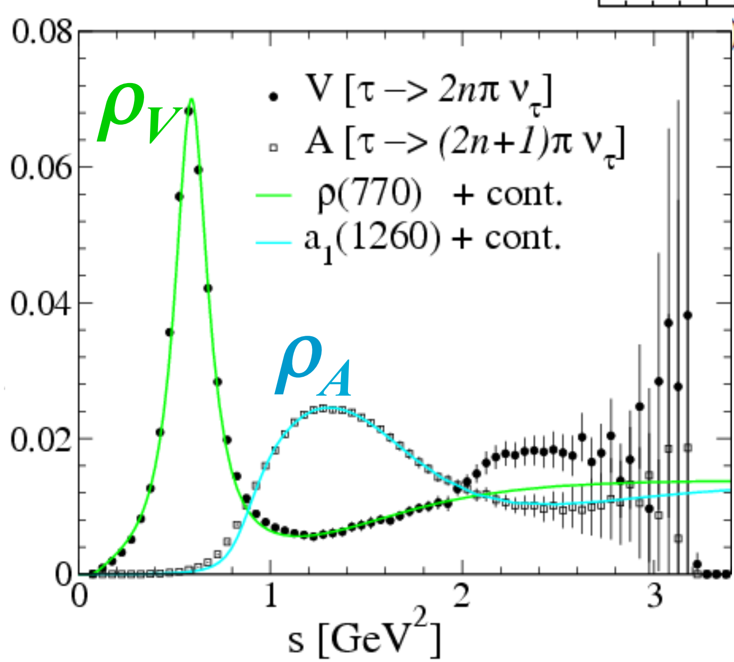


Vector-Axial vector splitting (also pseudoscalar-scalar) in the physical vacuum due to spontaneous breaking of chiral symmetry

Chiral symmetry restoration

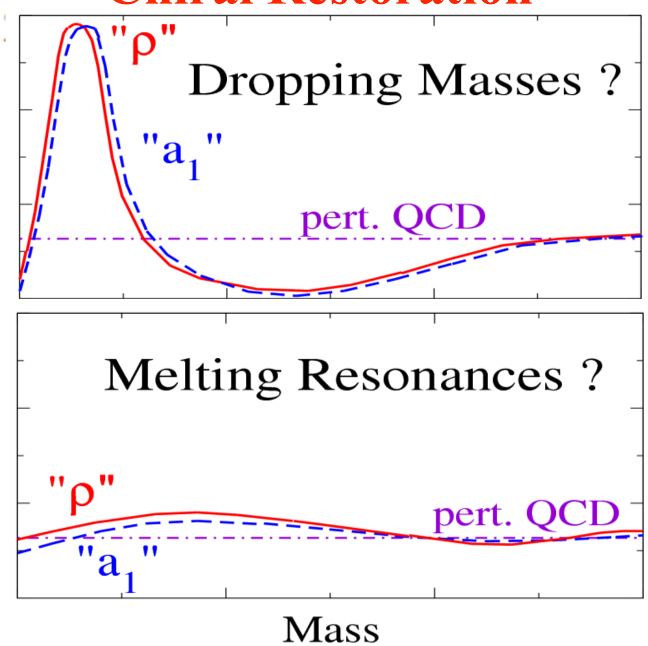


Vacuum



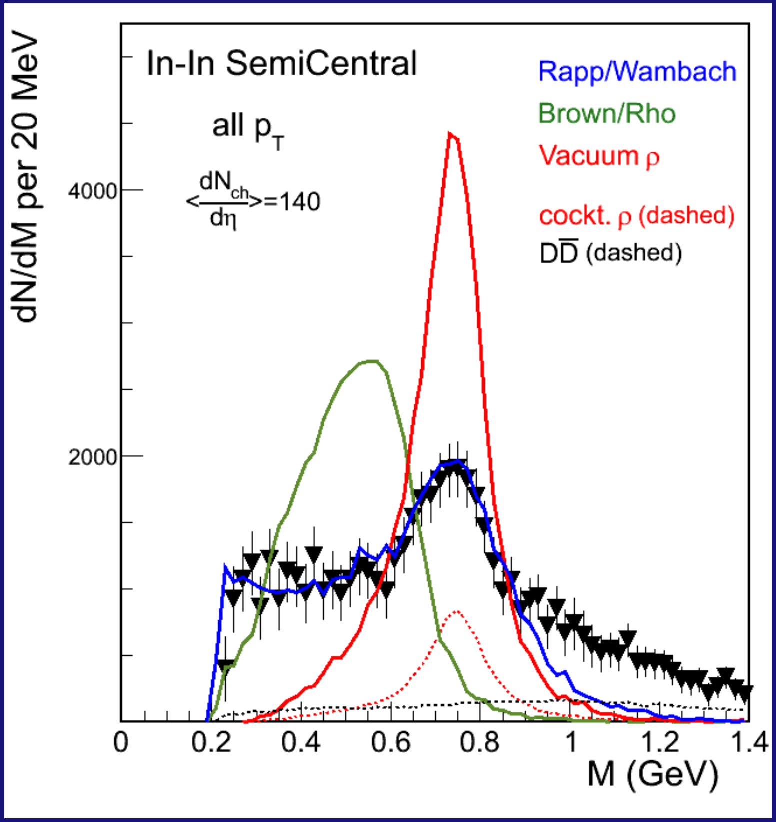
$$\int \frac{ds}{\pi}(\rho_V - \rho_A) = -m_q\langle\bar{q}q\rangle$$

Chiral Restoration



Towards chiral restoration: ρ melting

PRL 96 (2006) 162302; AIP Conf.Proc. 1322 (2010) 1



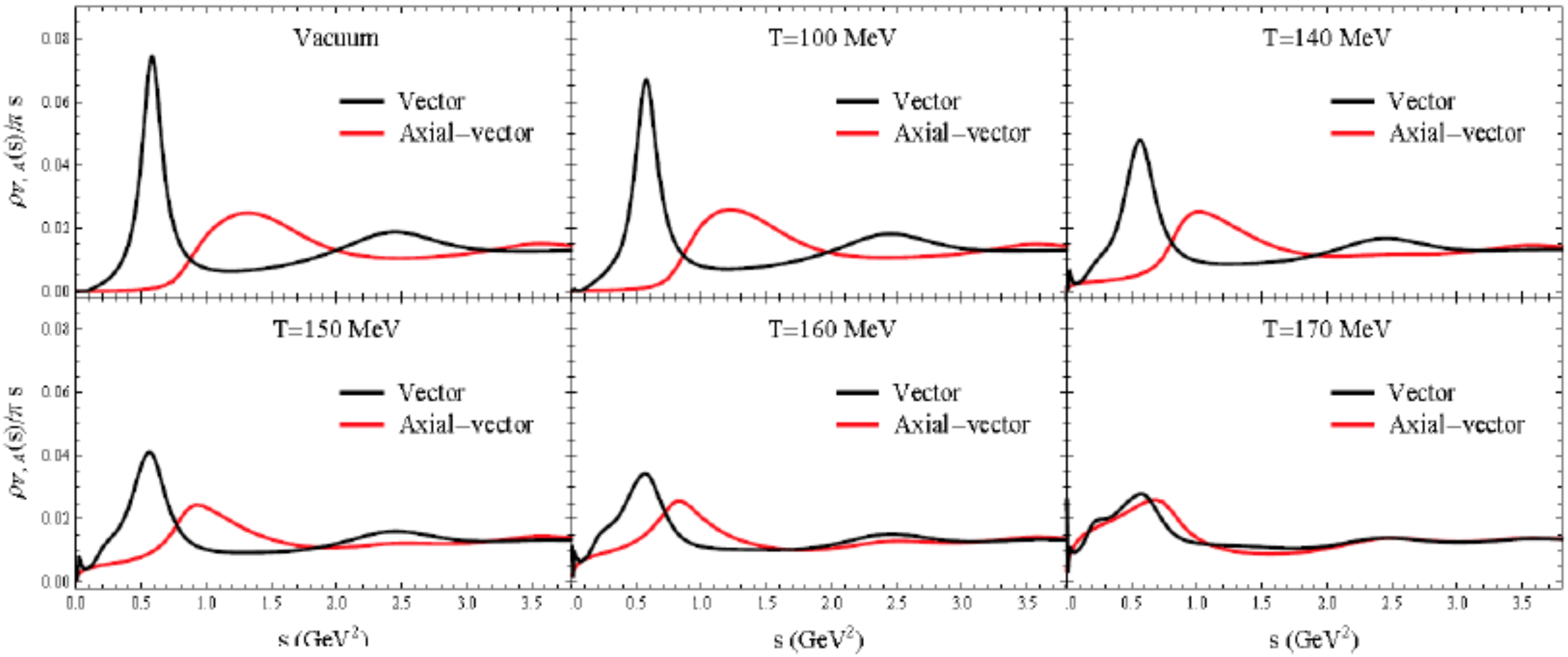
- NA60 In-In 160 AGeV - data before acceptance correction
- Comparison to theoretical models:
  - Brown/Rho - dropping mass scenario
  - Rapp/Wambach – only broadening

Strong broadening of ρ observed (no mass shift) → 'hadrons melt'
(indirect) evidence of chiral symmetry restoration

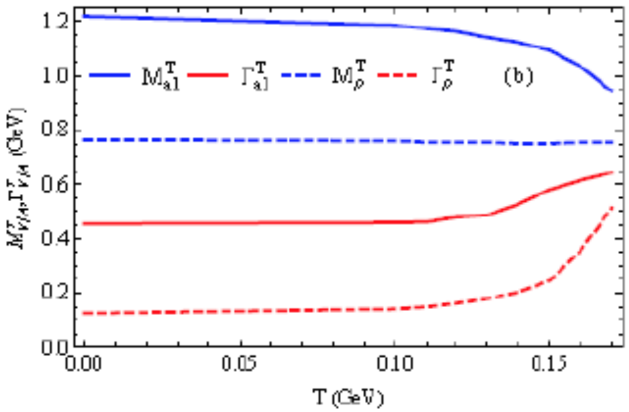
On chiral restoration and ρ melting*: P.M.Hohler and R. Rapp, PLB 731 (2014) 103*

a_1 spectral function in the medium

Hohler, Rapp, PLB 731 (2014) 103



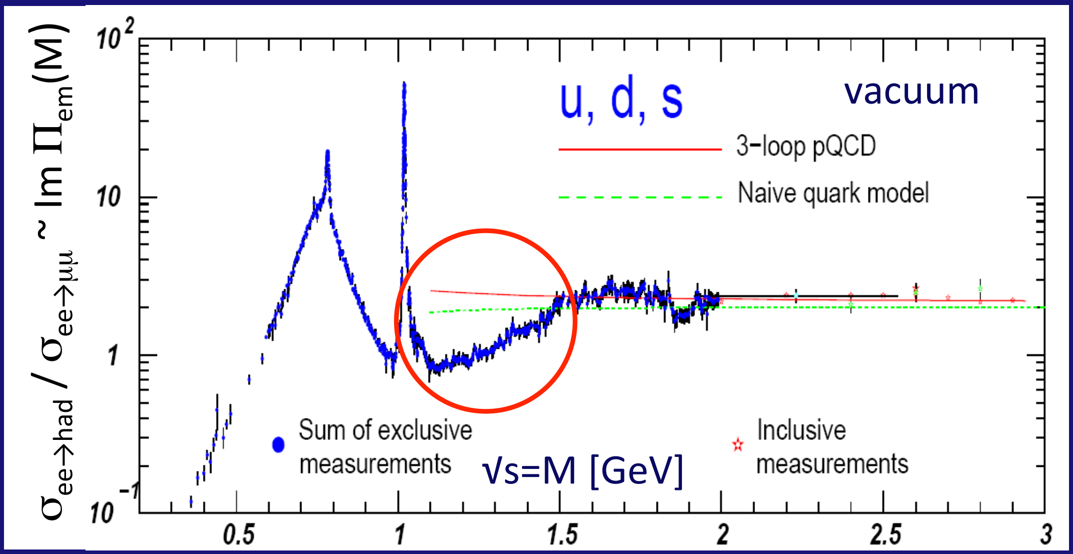
PMH and Rapp (2014)



V - AV mass degeneracy → Chiral symmetry

Resonance melting → Deconfinement

a_1 and dileptons : vacuum vs medium



Axial states don't couple to virtual photons

In vacuum (left) dip the region M=1-1.5 GeV: significant depletion

In the medium: chiral mixing

To lowest order in T pion induced mixing of vector and axial-vector correlators:

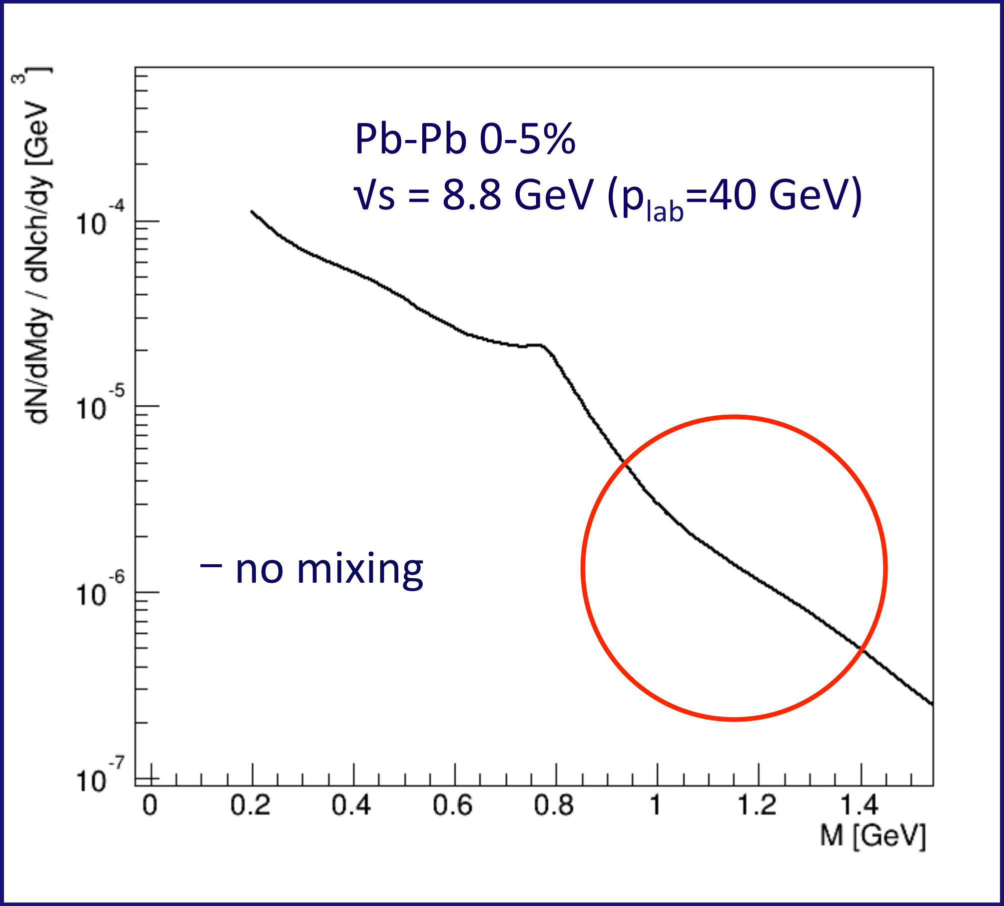
$$\Pi_V(T) = (1-\varepsilon)\Pi_V(T=0) + \varepsilon\Pi_A(T=0)$$

$\varepsilon = T^2/6f^2_\pi$

The admixture of the a_1 resonance, via the axial-vector correlator, thus entails an enhancement of the dilepton rate for M ~ 1 – 1.4 GeV

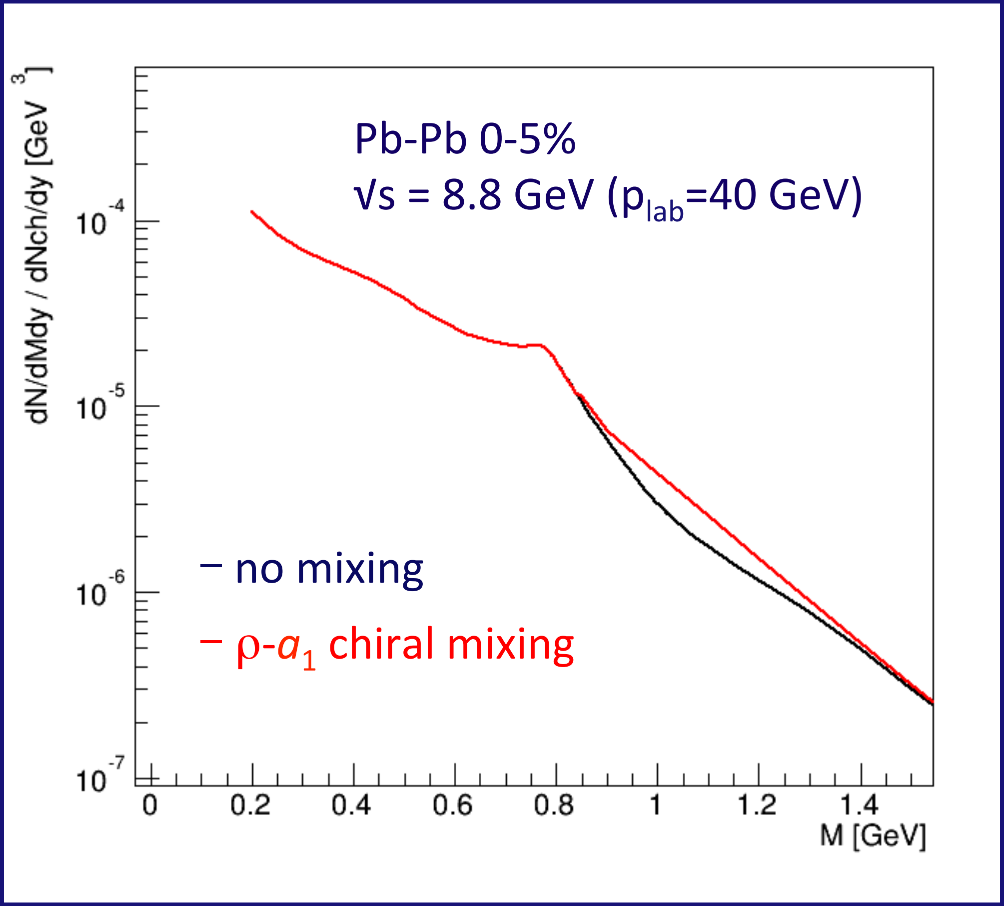
Dileptons and the dip

In medium ρ + ω + QGP – no chiral-mixing (ε = 0)



Dileptons and chiral mixing

In medium ρ + ω + QGP + maximal chiral mixing (ε = 1/2)

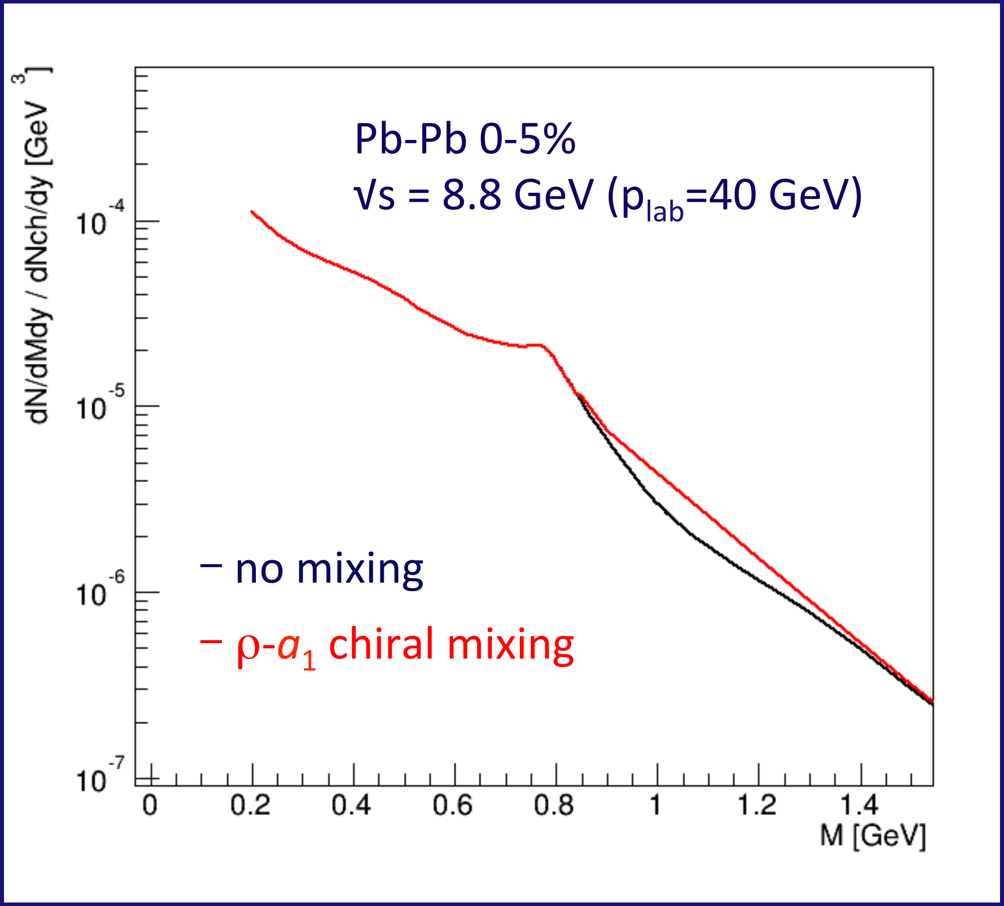


20-30% effect in yield for 1<M<1.5 GeV

Maximal effect: ε = 1/2 all over fireball evolution (refinement of theory calculation needed)

Dileptons and chiral mixing: measurement

In medium ρ + ω + QGP + maximal chiral mixing (ε = 1/2)



20-30% effect in yield for 1<M<1.5 GeV

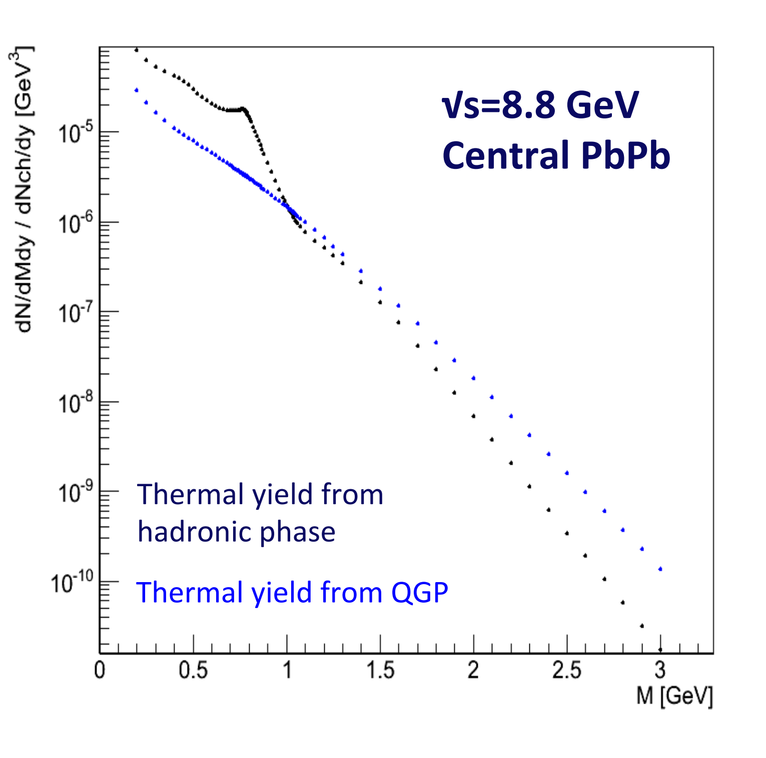
Maximal effect: ε = 1/2 all over fireball evolution (refinement of theory calculation needed)

Experiment:

- Delicate measurement
- Low energy: probe matter close to phase boundary (knowledge from T measurement) to disentangle from QGP
- Low energy: DDbar negligible
- Drell-Yan: reference measurements in pA

Performance study for thermal radiation Pb+Pb 0-5% central collisions at √sNN=6.3, 8.8, 17.3 GeV: dilepton generators

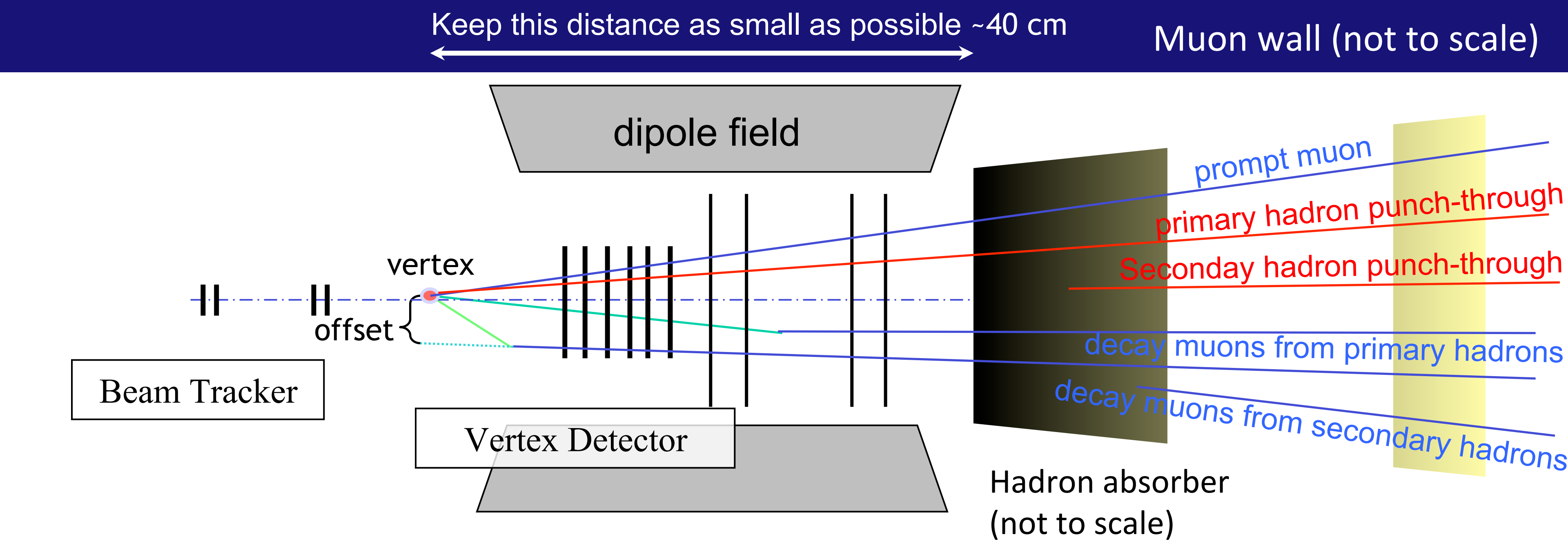
Hees, Rapp PLB 753 (2016) 586



- **Thermal radiation generator** based on calculation provided by R. Rapp, H. Hees:
  - dileptons from hadronic phase based on the in-medium ρ+ω
  - IMR with/without chiral mixing
  - dileptons from QGP phase based on lattice QCD constrained rate
- **Hadronic cocktail generator** (physics background):
  - derived from NA60 Genesis using statistical model (Becattini et al.); $dN_{ch}/d\eta=270$
- **Drell-Yan and open charm** (physics background)
  - estimated with Pythia

N.B.: sensitivity to chiral mixing: comparison of performance mass spectra with theoretical expectation assuming full chiral mixing

Simulation of combinatorial background

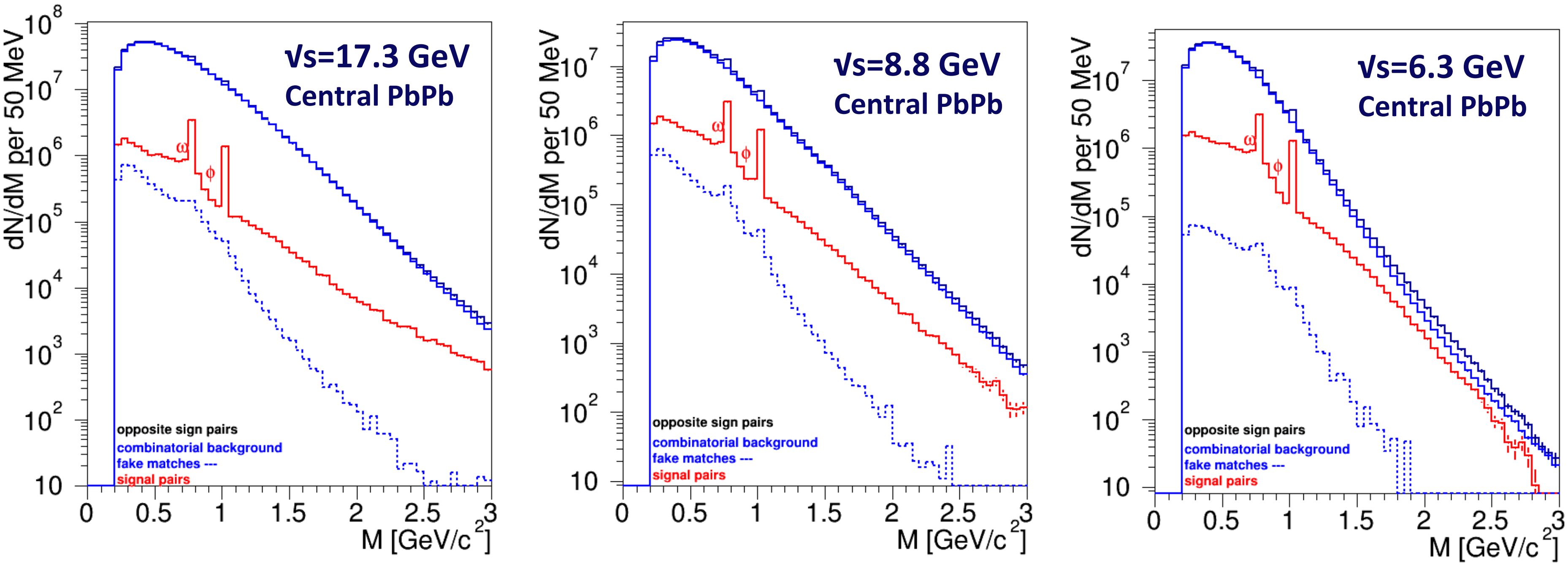


- Combinatorial background:
  - The most important aspect to consider to assess the physics performances

- Fluka simulations:
  - Full hadronic shower development in absorber
  - Punch-through of primary and secondary hadrons (p, K, π)
  - Muons from secondary hadrons

Performance for thermal dimuons in Pb+Pb: data samples

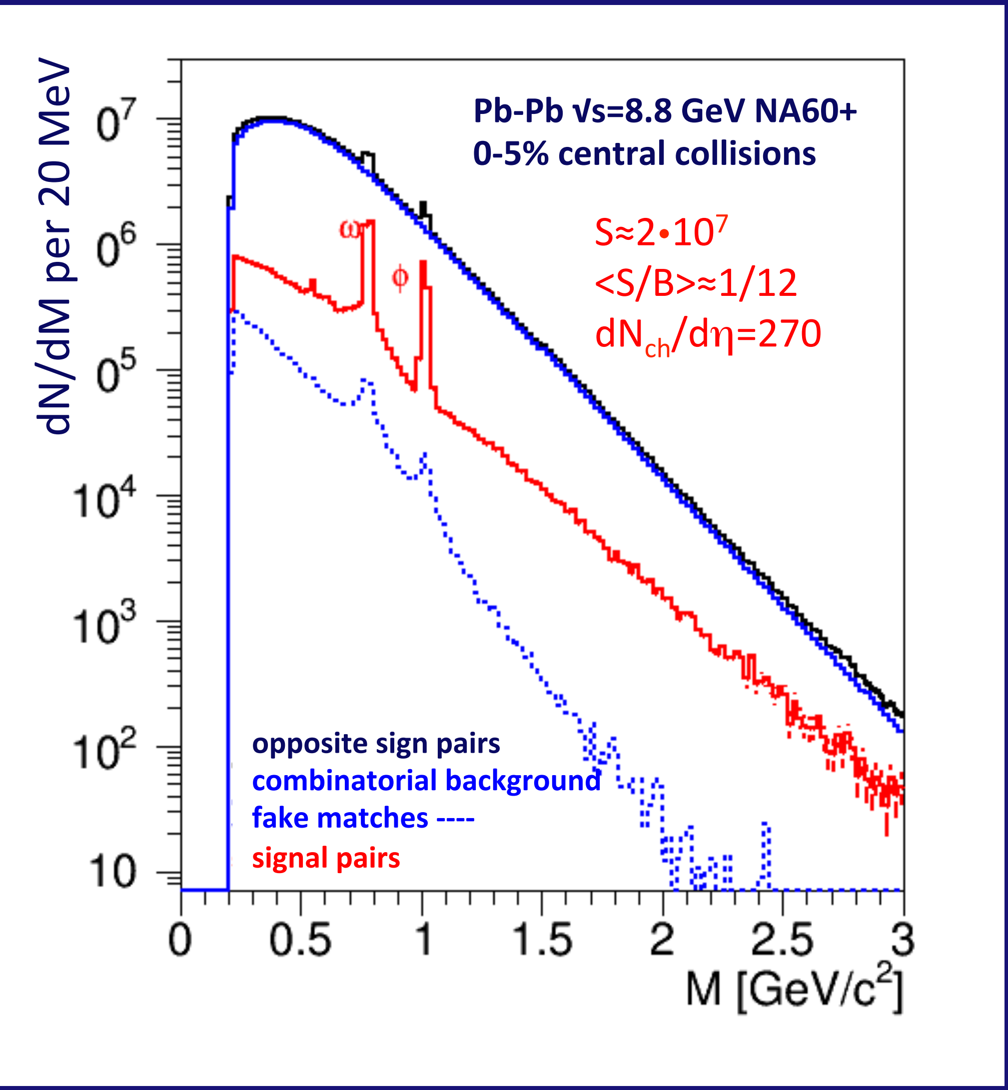
Yields based on thermal dimuon estimate from Rapp-Hees PLB 753 (2016) 586, DDbar and Drell-Yan from Pythia, statistical model for low mass resonances



decreasing energy (Elab=160→20 GeV)

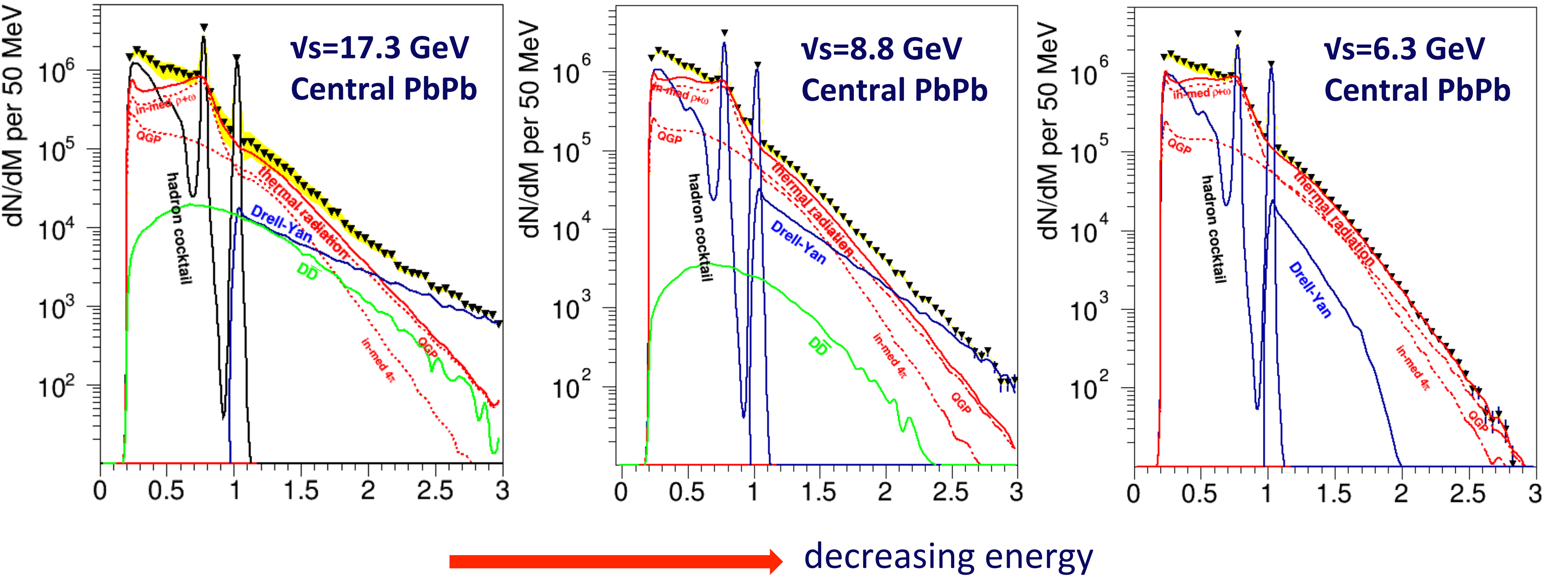
- 2 · 10^7 reconstructed signal pairs in 0-5% central events
  - → ~5 · 10^7 events in 0-100%
  - → factor 100 over NA60
- Statistics collected in a ~4 weeks run at each energy with 1 MHz interaction rate

NA60+ performance for thermal radiation in central Pb+Pb : data sample size and quality ($\sqrt{s}$=8.8 GeV; E_{lab}=40 GeV)



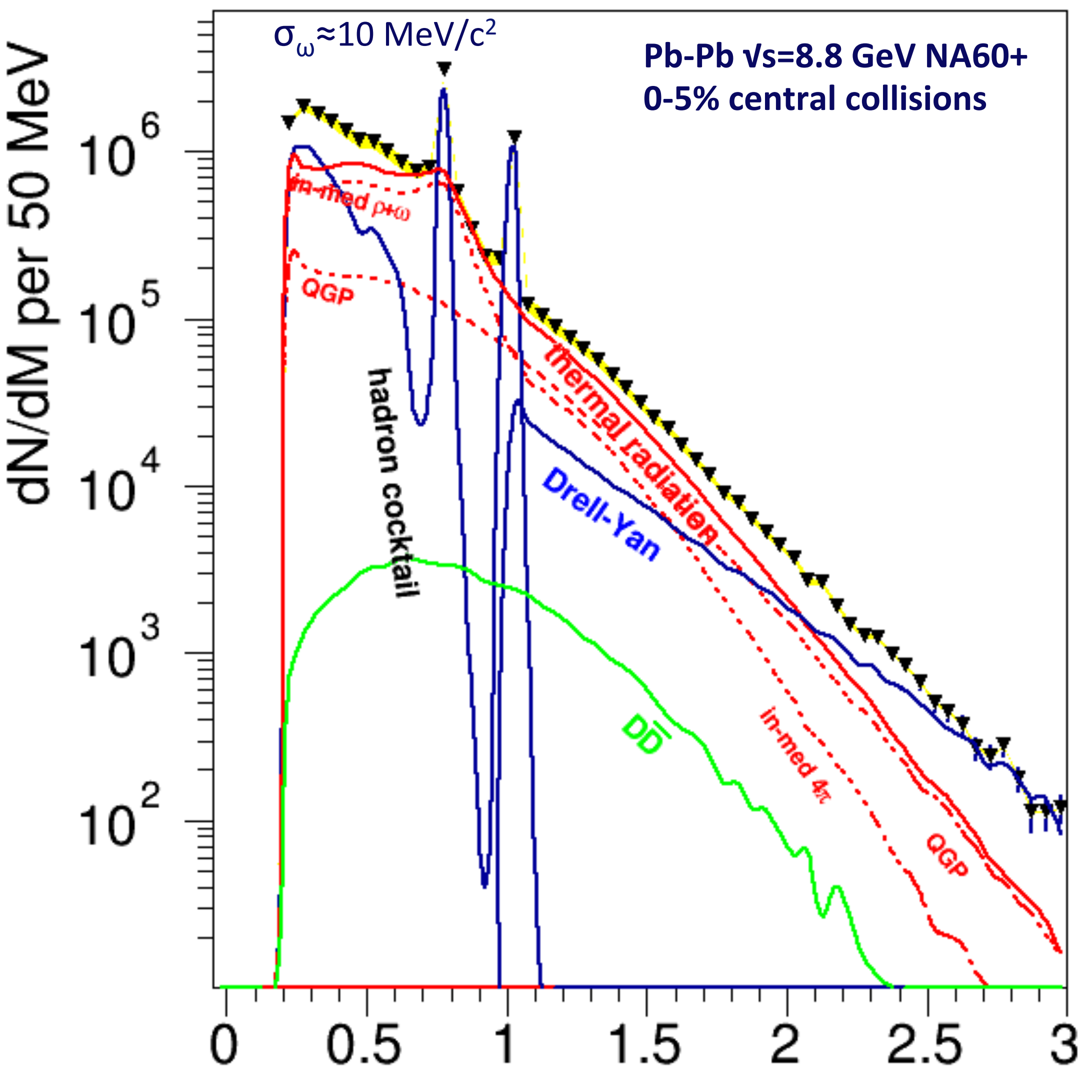
- $2 \cdot 10^7$ reconstructed signal pairs - factor 100 over NA60
- Combinatorial background: μ from π,K or hadron puch-through - B/S similar as in NA60
- Fake matches: signal μ matched to wrong track in pixel telescope - much better than NA60
- Mass resolution 10-15 MeV - factor ≈2 better than NA60

Signal mass spectra vs √s



- From full SPS energy towards low energy:
  - Significant reduction of Drell-Yan
  - Open charm becomes negligible
  - Decrease of QGP

Signal mass spectrum: example for central Pb+Pb at √s=8.8 GeV

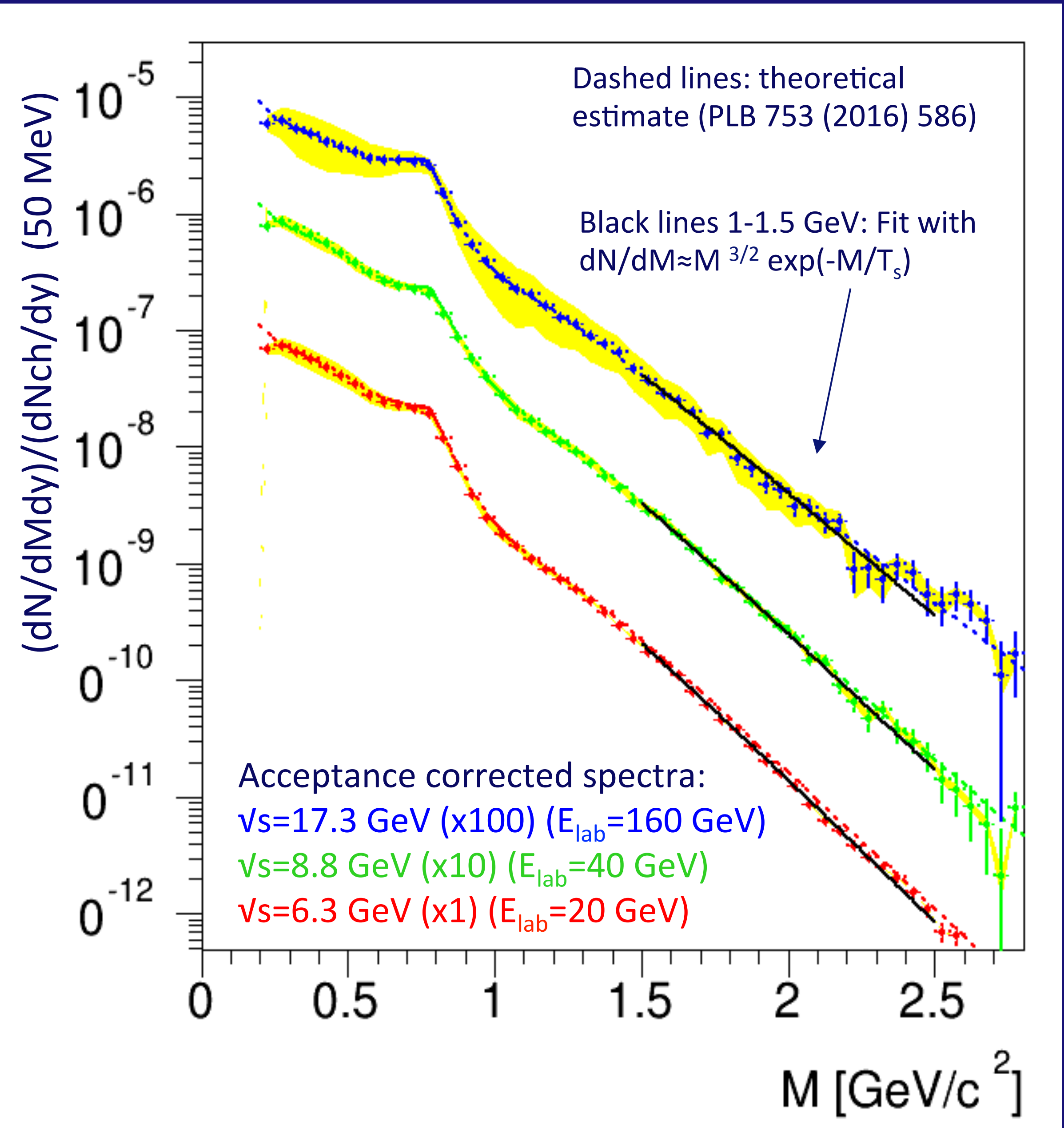


- Signal spectrum after subtraction of:
  - comb. bkg (0.5% precision)
  - fake matches

- Dilepton sources M<1 GeV:
  - Thermal radiation ρ+ω
  - Thermal radiation QGP
  - Freeze-out hadron cocktail (η, ω, ϕ) (M<1 GeV)

- Dilepton sources M>1 GeV:
  - Thermal radiation 4π
  - Thermal radiation QGP
  - Drell-Yan
  - Open charm

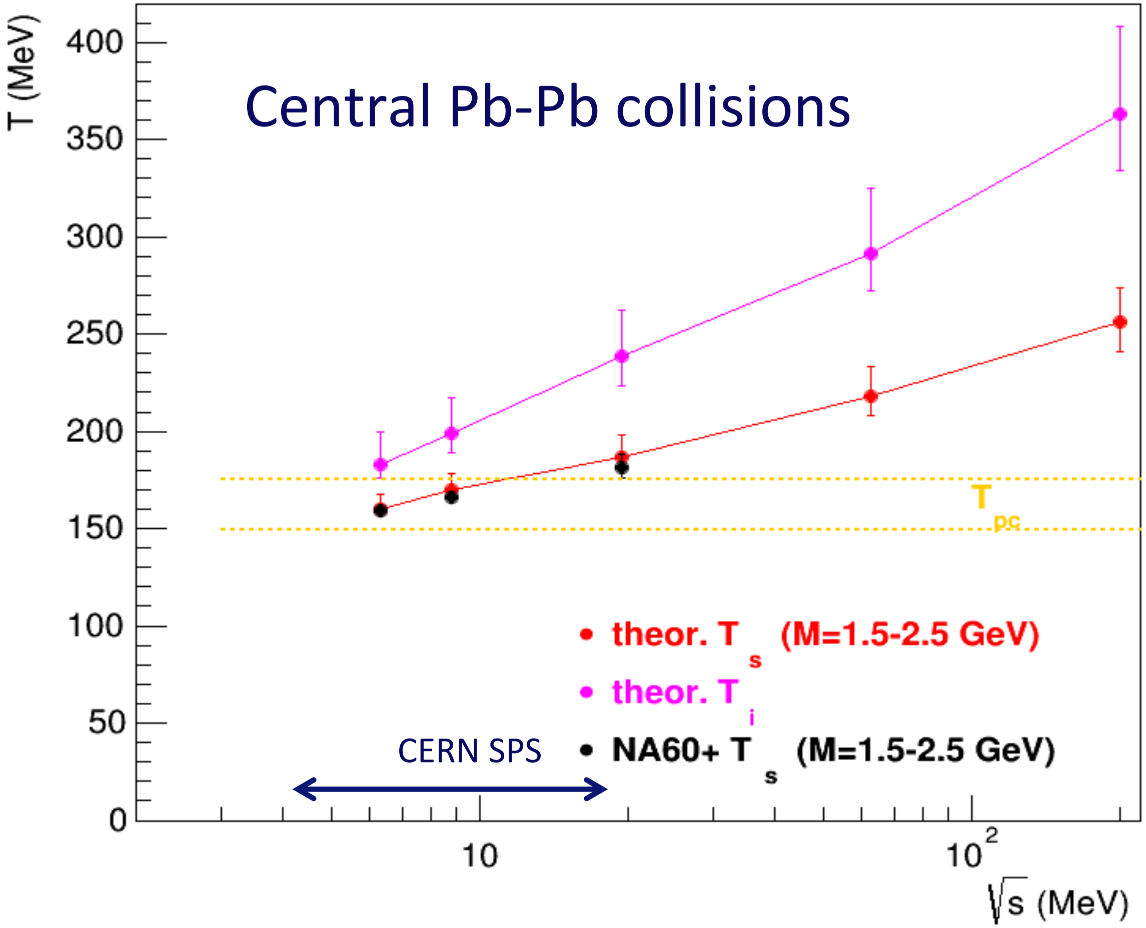
ρ-a_1 chiral mixing and temperature from thermal spectra



- Thermal spectra: acceptance corrected spectra after subraction of:
  - Freeze-out cocktail
  - Open charm
  - Drell-Yan
- Temperature:
  - 1.5<M<2.5 GeV fit to dN/dM≈M $^{3/2}$exp(-M/T_s)
  - Systematic uncertainty: vary bkg subtraction by 0.5% before fitting

A precise measurement of a caloric curve in high-energy nuclear collisions: NA60+ performance

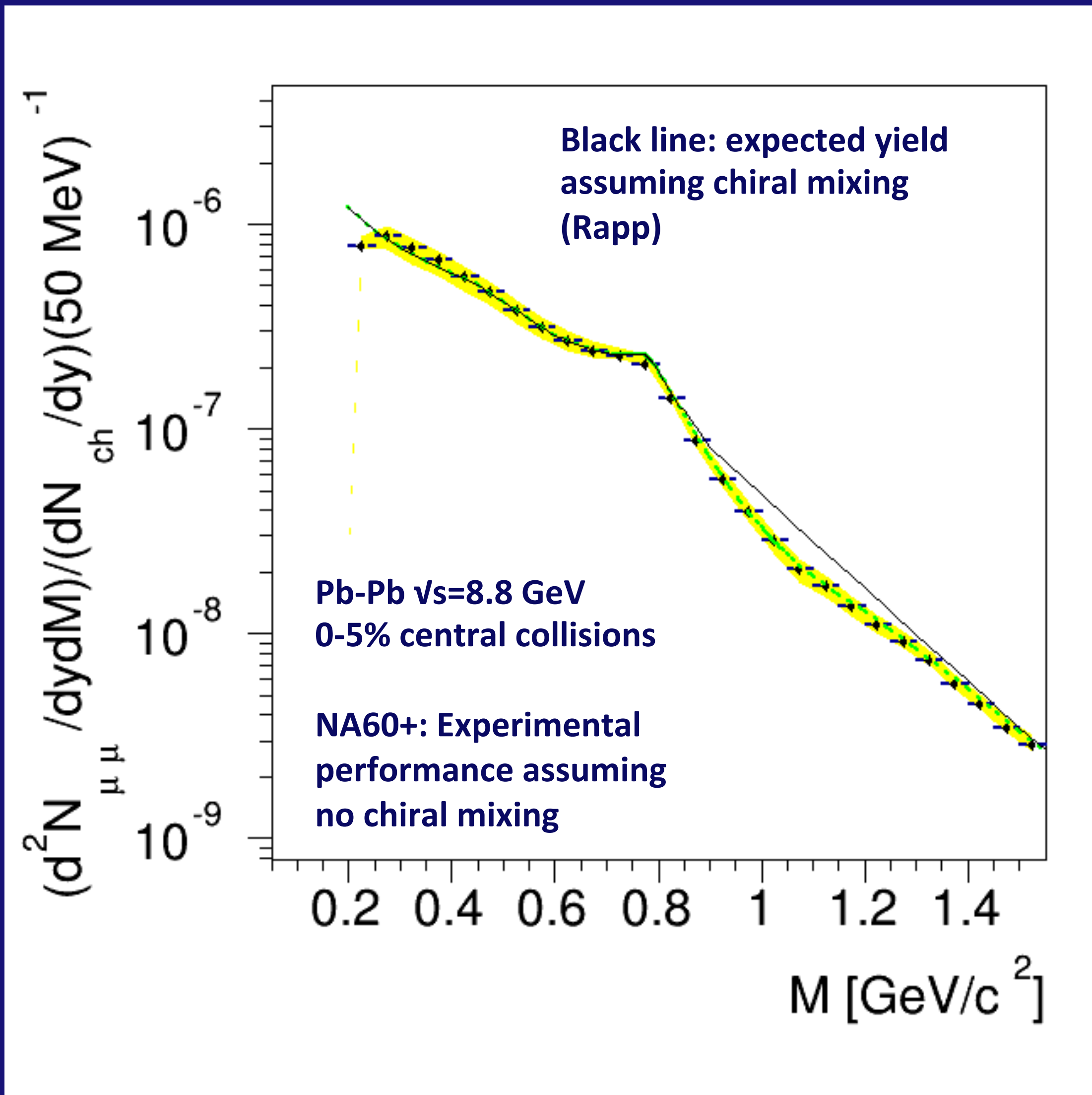
Theoretical estimates from Rapp, van Hees PLB 753 (2016) 586



- First order hadron gas-QGP phase transition:
  - energy range below √s=10 GeV important to map out this transition regime (as suggested by this theoretical model)
- Black points: NA60+ measurement of T_s from fit of thermal spectra for 1.5<M<2.5 with $dN/dM \approx M^{3/2} exp(-M/T_s)$

- High precision: at low energy T measurement with errors at MeV level (% level)
  → strong sensitivity to possible flattening

Prospects for measuring ρ-a_1 mix: NA60+ performance



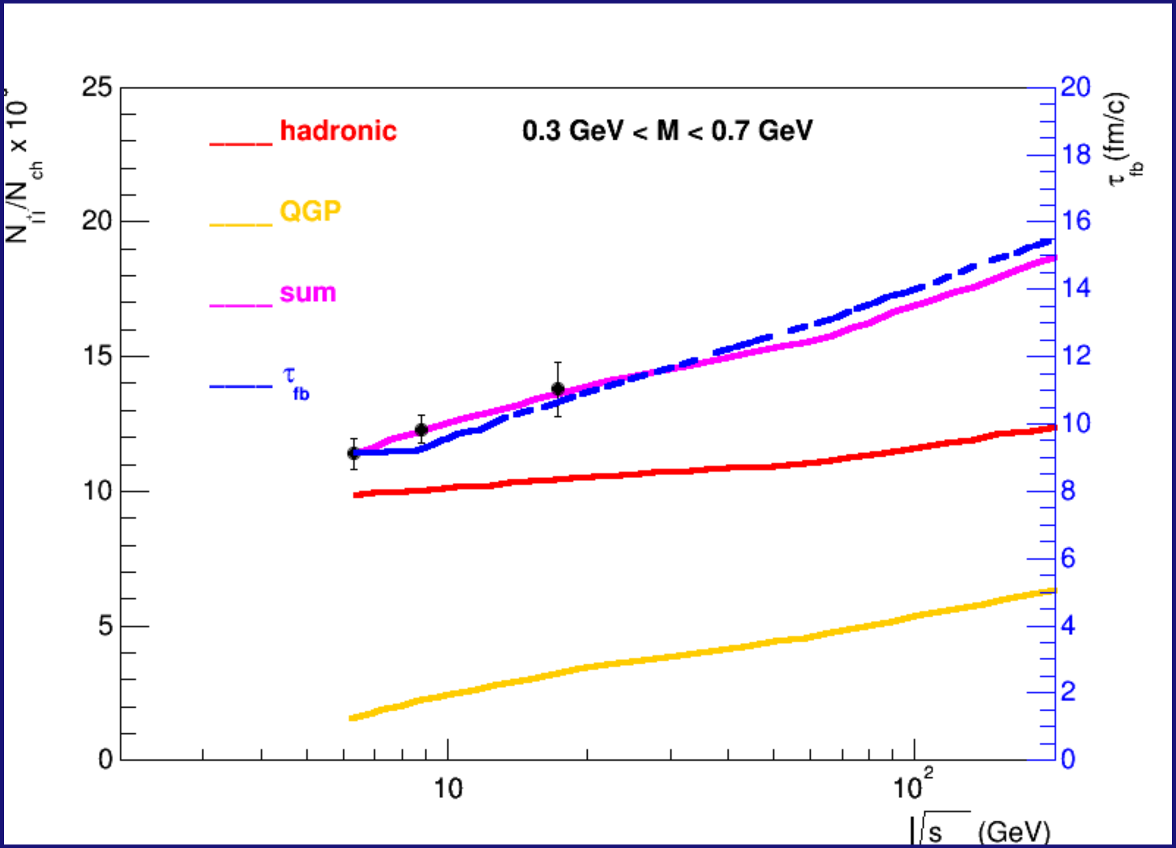
Chiral mixing: yield enhancement in 1<M<1.5 GeV

Measurement challenging, but sensitivity to enhancement!

Sensitivity might improve further at √s=6.3 GeV (needed theoretical input)

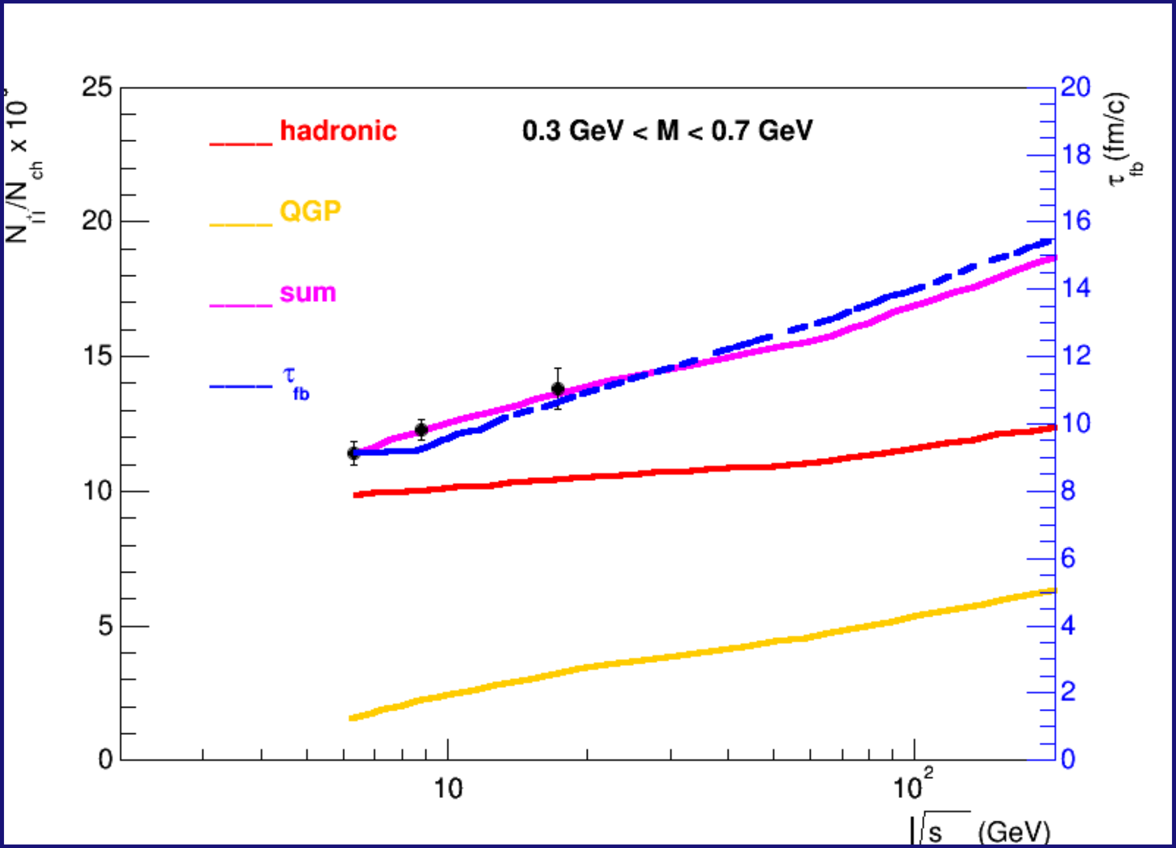
Dilepton excitation function and fireball lifetime: NA60+ performance

Uncertainty dominated by combinatorial bkg subtraction (0.5% uncertainty)



Dilepton excitation function and fireball lifetime: NA60+ performance

Uncertainty dominated by combinatorial bkg subtraction (0.35% uncertainty)



Charm and quarkonia

Open charm: physics motivations

- Characterize the QCD medium with open heavy flavours
  - Test models which predict strongest in-medium interactions in the vicinity of the quark-hadron transition [1]
  - Sensitivity to the role of hadronic interactions [1]
  - Enhancement of charm production at chiral restoration where the threshold for production of a D-Dbar pair may be reduced [2]

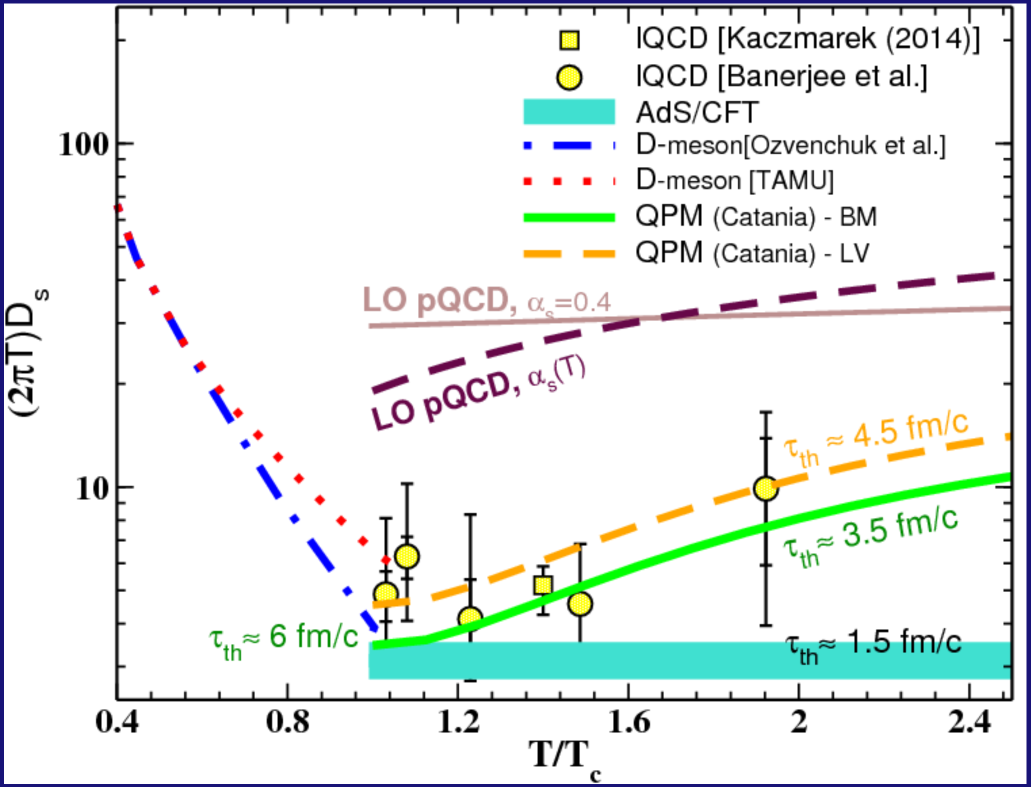
- Charm cross section as reference for charmonia

- Can be addressed via measurements of:
  - D-meson yield and elliptic flow in A-A collisions
    - New energy domain
  - "Charm hadrochemistry" in p-A and A-A collisions
    - Baryon-to-meson ratios via Λ_c/D^0
      - Interesting also in p-A since Λ_c/D^0 in pp (p-Pb) at LHC is higher than in e^+e^-
    - Strangeness production via D_s/D

[1] R. Rapp, private discussion
[2] B. Friman et al. Lect. Notes Phys. 814 (2011) pp. 980

Charm diffusion coefficient

Phys. Rev. C96 (2017) 044905

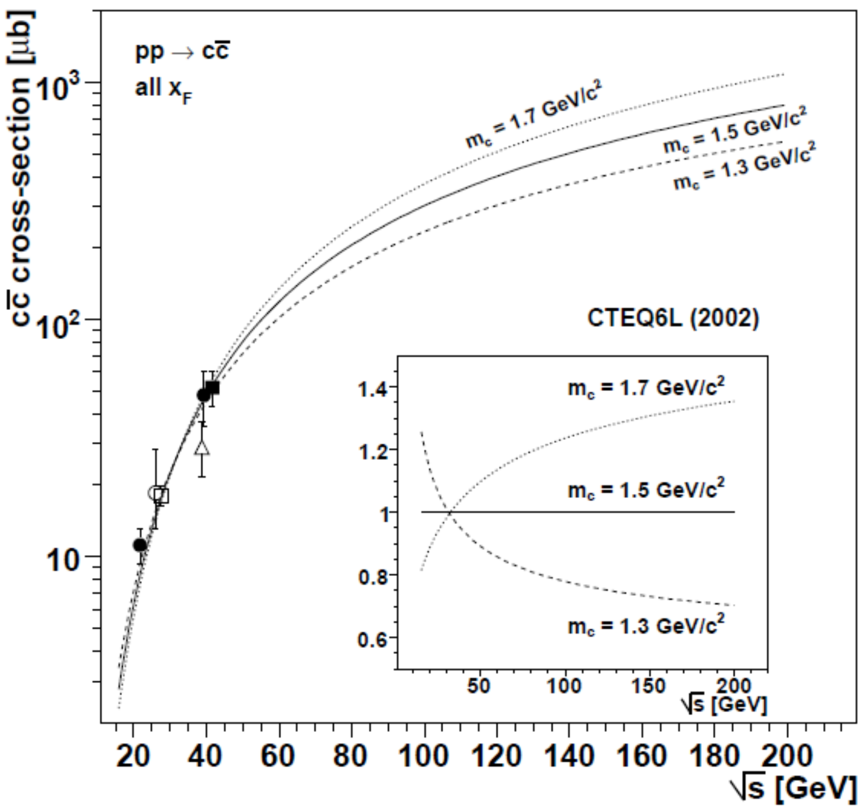


- Charm diffusion coefficient predicted larger in the hadronic phase for T➔Tc than in QGP for T➔Tc
- low energy: higher sensitivity to diffusion coefficient in hadronic phase (important input also at collider energies)

Charm cross section in pp/p-A

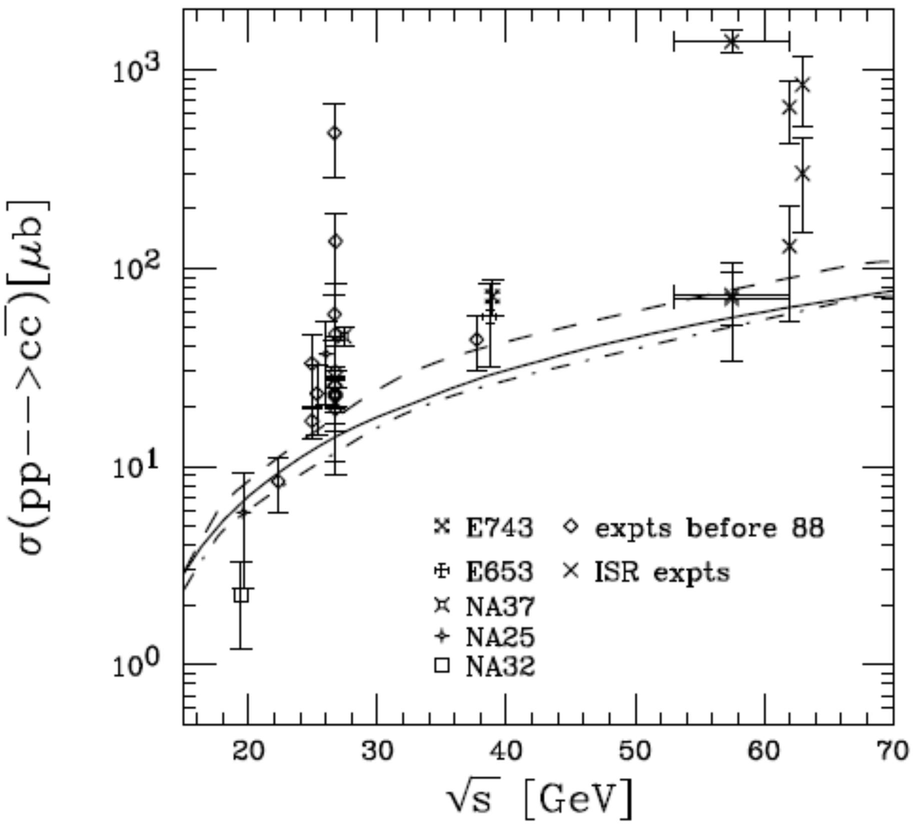
Total charm cross section at √s<20 GeV experimentally poorly known

PYTHIA LO cross sections scaled with appropriate K-factor



C. Lourenco, H. Wohri, arXiv:hep-ph/0609101

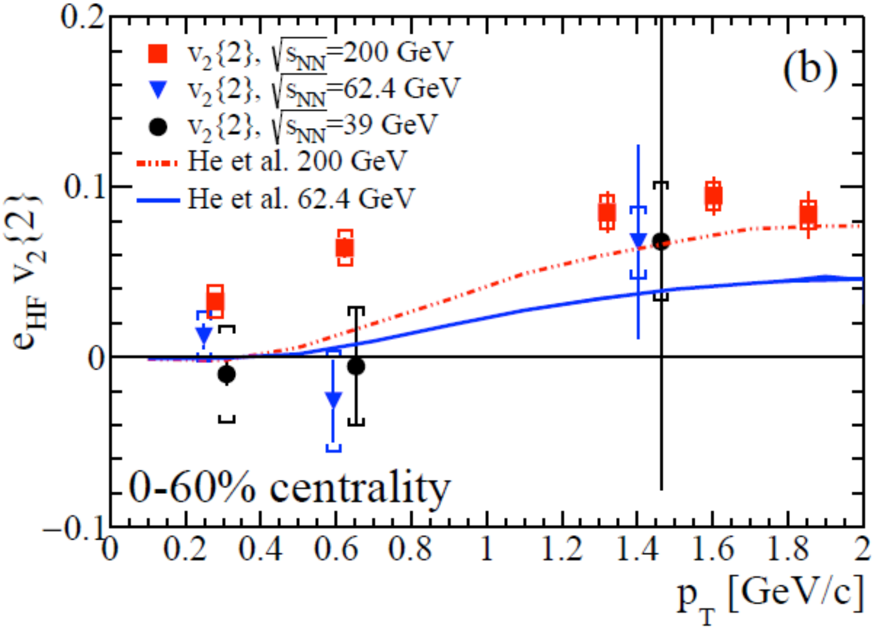
MNR calculations with m_c=1.2 GeV and μ=2m_c



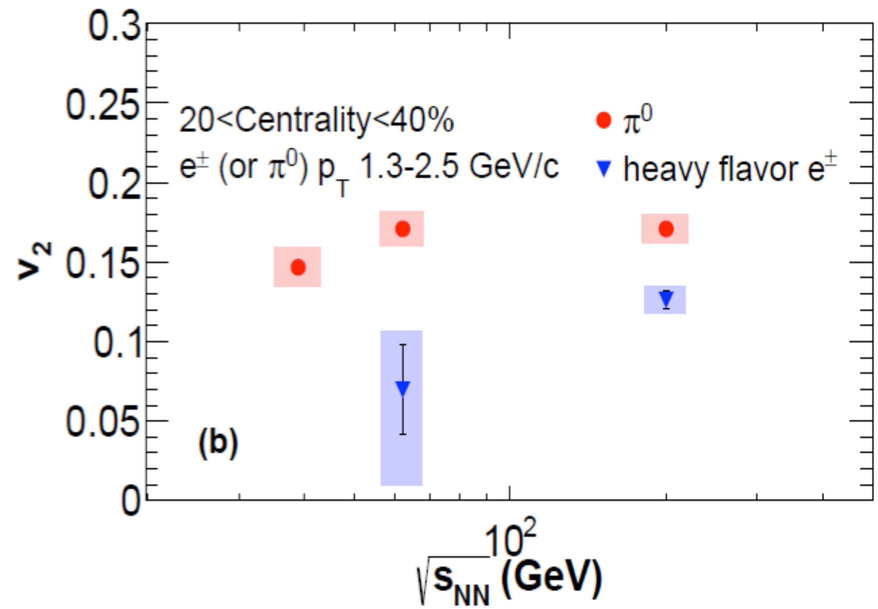
R. Vogt, arXiv:hep-ph/0111271

Elliptic flow

- Measurements of HF-decay electron v_2 at √s=39 and 62 GeV/c from RHIC BES
  - Smaller v_2 than at √s=200 GeV
  - Not conclusive on v_2>0



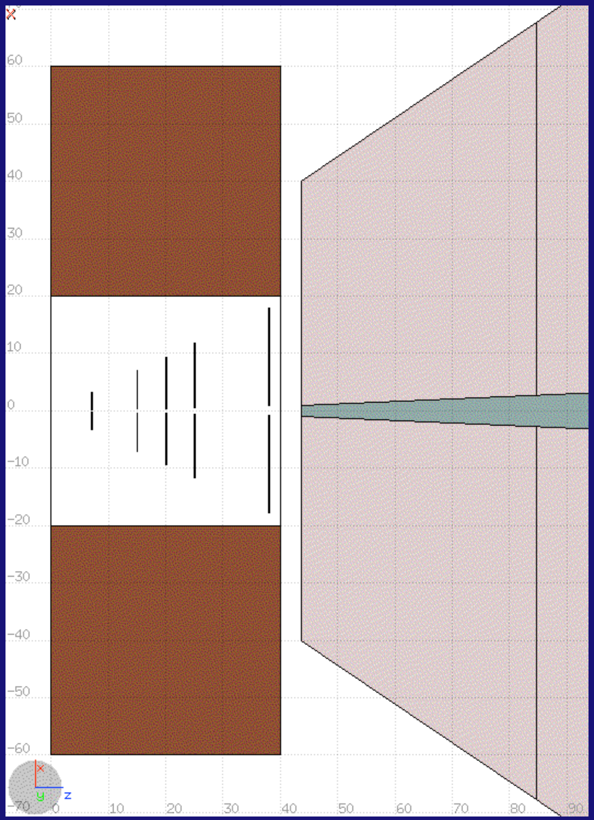
STAR, PRC 95 (2017) 034907



PHENIX, PRC 91 (2015) 044907

Performance studies for NA60+

- $D^0 \rightarrow K\pi$ as benchmark
  - Studies on 3-prong decays of D^+, D_s^+ and Λ_c will follow
- K and π reconstructed in the vertex spectrometer
- Fast simulation of track reconstruction performance
- Background reduction with selections on displaced decay vertex topology
- Estimate S/B, significance
- Two beam energies considered



E_{beam} (AGeV)	$\sqrt{s_{NN}}$ (GeV)
160	17.3
60	10.6

Signal simulation

- Decay $D^0 \rightarrow K\pi$ simulated
  - p_T and y shapes from POWHEG-BOX+ PYTHIA6

- Fast simulation of detector response
  - Pixel efficiency assumed to be 100%
  - Underlying event simulated → reasonable detector occupancy
  - Two configurations for 5 layers of pixels
    - Hybrid
      - Point resolution: 10 μm
      - Material budget per layer: 400 μm Si, 1000 μm C
    - Monolithic
      - Point resolution: 5 μm
      - Material budget per layer: 100 μm Si

- Decay vertex reconstruction from the DCA points of the daughter tracks
  - Track covariance matrix elements used as weights

Signal vs. background

- Number of $D^0 \rightarrow K\pi$ decays per event
  - $N_{signal} = \sigma_{cc} * T_{AA} * BR(D^0 \rightarrow K\pi) * f(c\text{->}D^0) * 2$
    - BR=3.89% ; $f(c\text{->}D^0)=0.55$
    - For 0-5% centrality: $T_{AA} = 26.9\ mb^{-1}$
    - For E_{beam}=160 GeV: $\sigma_{cc} = 5\ \mu b$
  - $N_{signal} \sim 0.006$

- Background tracks:
  - Abundances and p_T and y distributions of π, K and p from parameterisation based on NA49 results
  - About 1200 particles per event -> produce about 350k candidates per event, out of which about 8k are in the D^0 invariant mass range

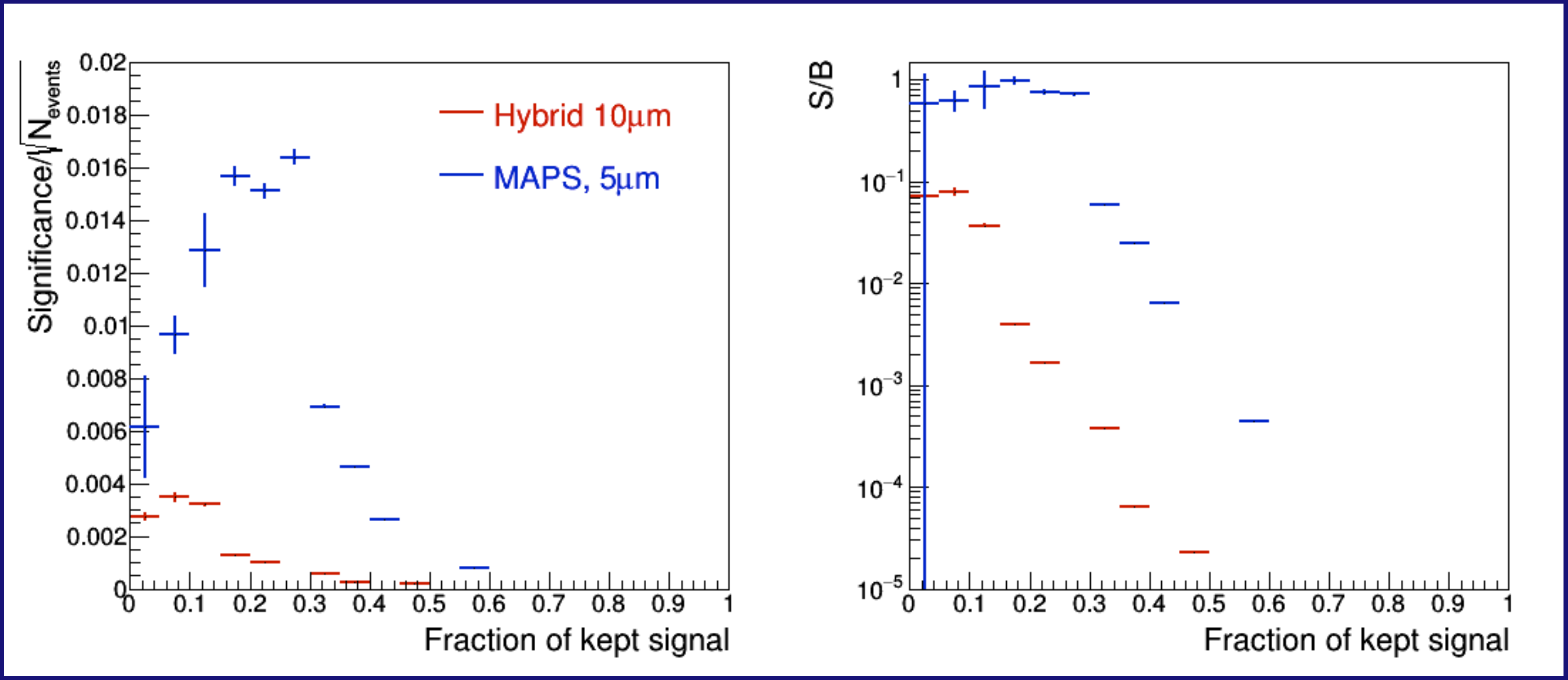
- ➔ S/B before selections is $\sim 0.006/8000 \sim 7 \cdot 10^{-7}$!

Candidate selection

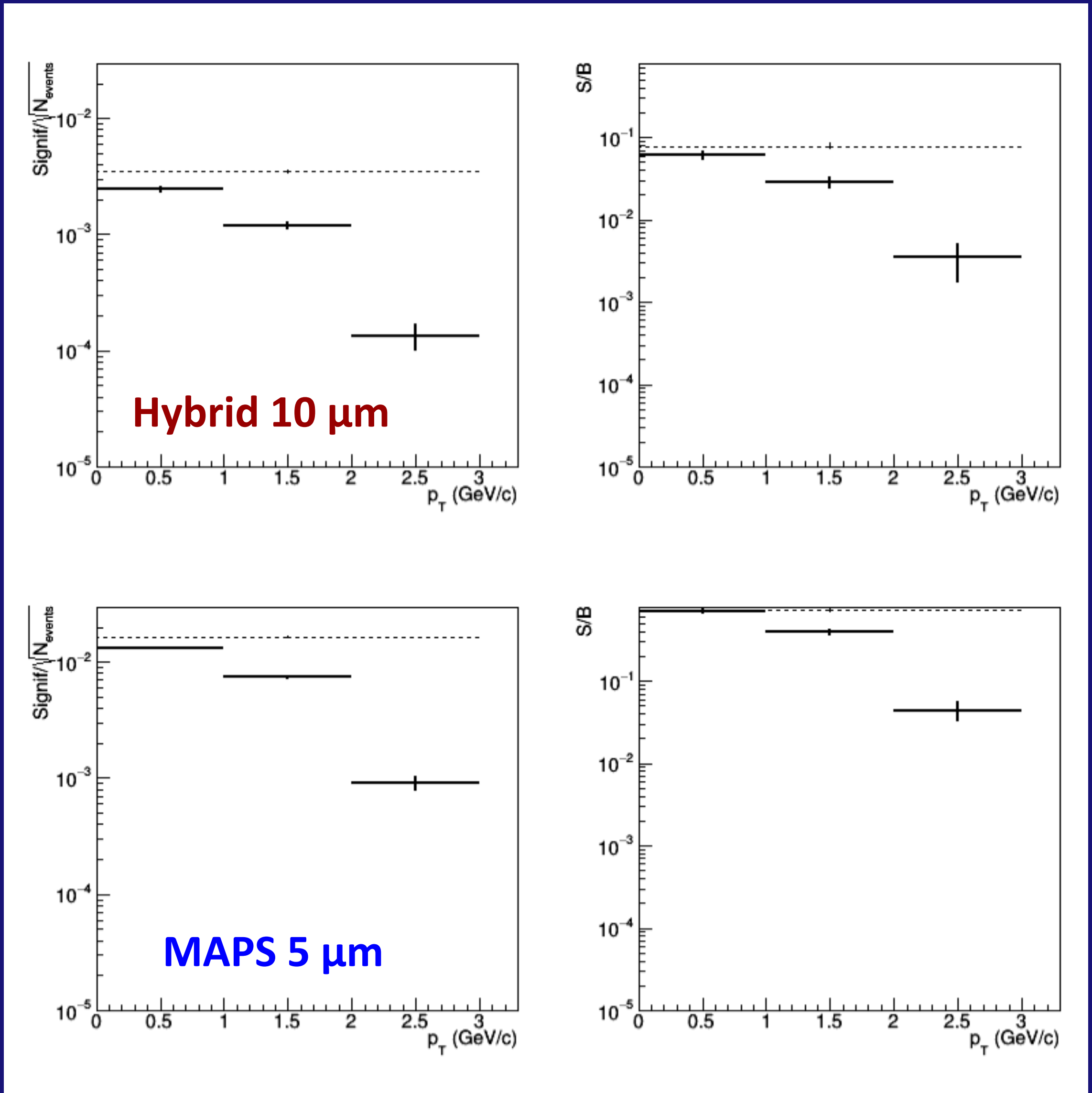
- Candidate selection needed to reduce the background
- Based on displaced decay vertex topology
- Cut variables:
  - Decay-track p_T
  - Cosine of ϑ^*
    - Angle between the K momentum in the D^0 rest frame and the D^0 flight line
  - Decay-track impact parameter (DCA to primary vertex)
  - DCA between decay (K and π) tracks
  - Product of decay-track impact parameters
  - Decay length (distance primary-secondary vertex)
  - Cosine of pointing angle
    - Angle between D^0 momentum and flight line

Selection

- Checked significance $[S/\sqrt{(S+B)}]$ signal-over-background [S/B] and D^0 efficiency with 400 different sets of cuts
  - Without binning in candidate p_T
- For each efficiency "bin" keep the set of cuts with maximal significance



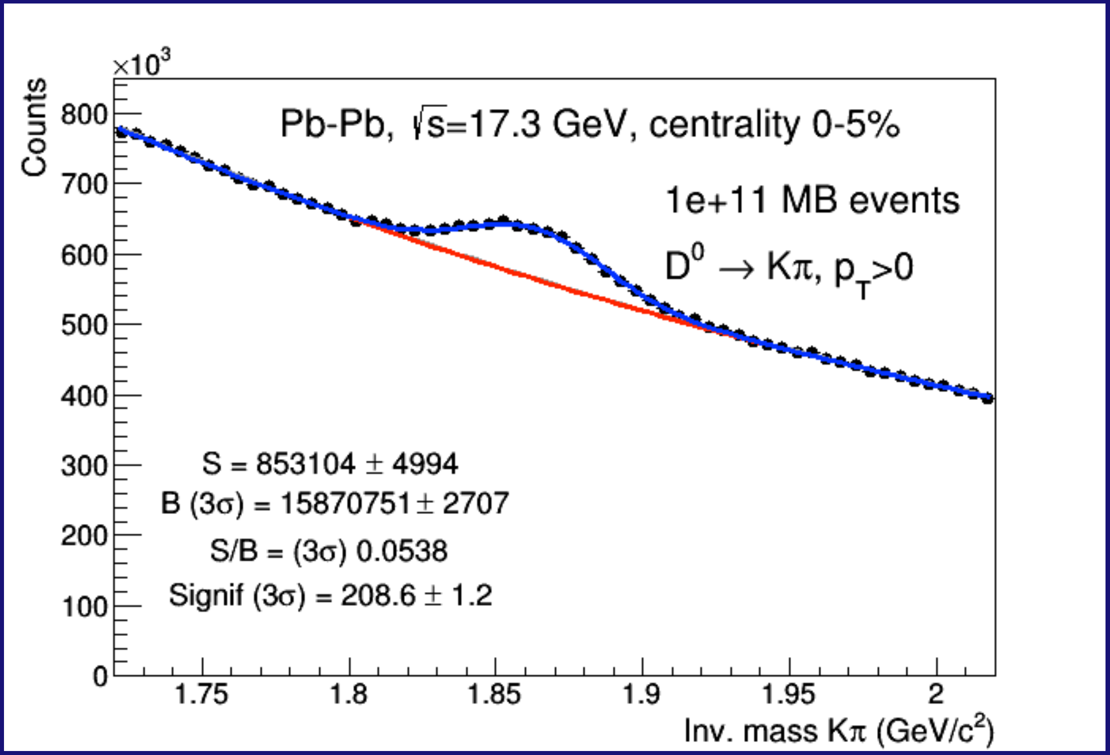
Significance and S/B



Performance with MAPS strikingly better than hybrids due to better resolution on:

- decay track momentum
- decay vertex position (10-15 μm vs 30-40 μm in the transverse plane)
- mass resolution (10 MeV vs 24 MeV)

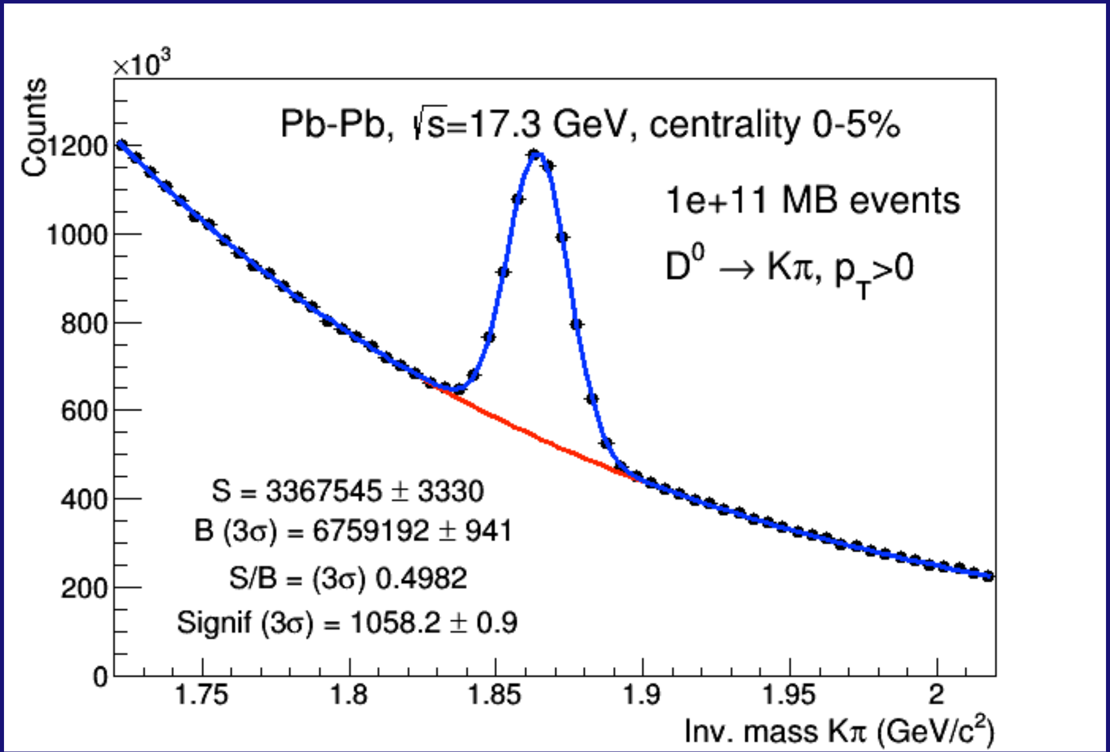
Invariant mass (Hybrid 10 μm setup)



Assuming:
σ_{cc} = 5 μb

- Projections for Pb-Pb at $\sqrt{s_{NN}}$=17.3 GeV, 0-5% centrality
- Assuming 10^{11} MB collisions (1 month at 150 kHz):
  - ~800k total reconstructed D^0

Invariant mass (MAPS 5 µm setup)



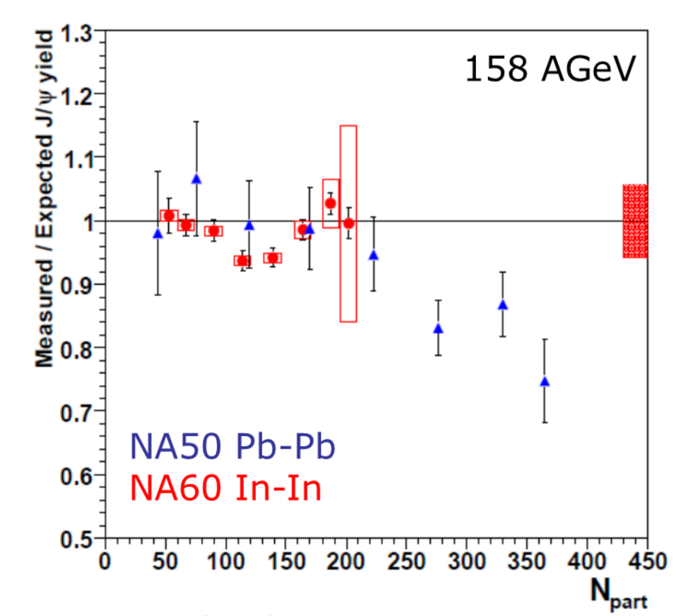
Assuming:
σ_{cc} = 5 µb

- Projections for Pb-Pb at $\sqrt{s_{NN}}$=17.3 GeV, 0-5% centrality
- Assuming 10^{11} MB collisions (1 month at 150 kHz):
  - ~$3 \cdot 10^6$ total reconstructed D^0
  - Allow for differential studies of yield and v_2 vs. p_T, centrality
- Performance for D^+, D_s^+ and Λ_c to be studied

Low-SPS energy charmonium production

- Extract information of the fundamental in-medium QCD force in the region of finite μ_B and at energy densities smaller than in the collider energy range

- Possible observables [1]:
  - Top SPS energy: J/ψ suppression compatible with feed-down effects from χ_c and $\psi(2S)$ → do direct J/ψ continue to survive at high baryon density ?
  - Can a sequential suppression be established (similarly to what done at LHC for the Υ) ?
  - Study the interaction of charmonia in confined matter via p-A collisions
    → separate hot and cold matter effects
    → investigate inelastic reaction rates in hadronic matter (small for J/ψ, possibly significant for χ_c and $\psi(2S)$)

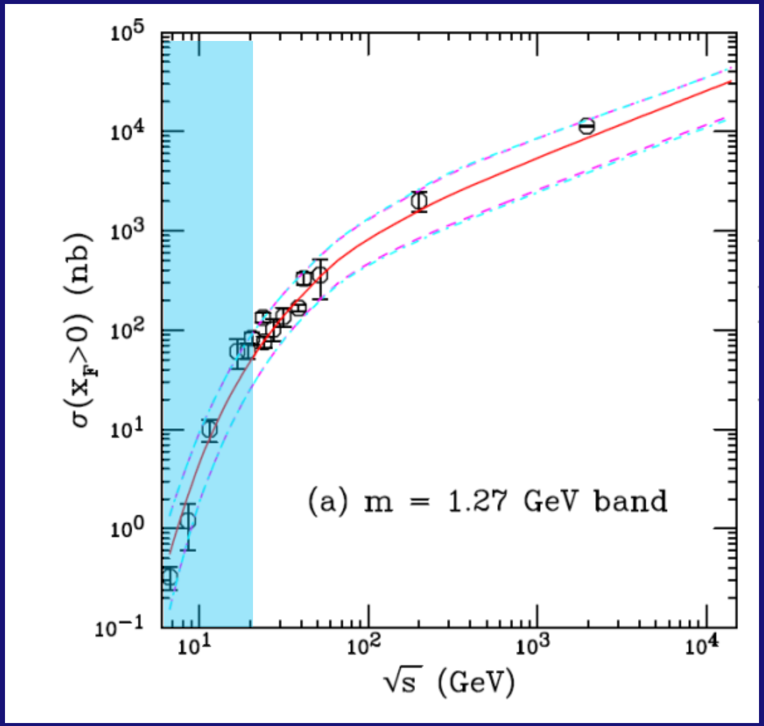


NA60, NPA830 (2009) 345c

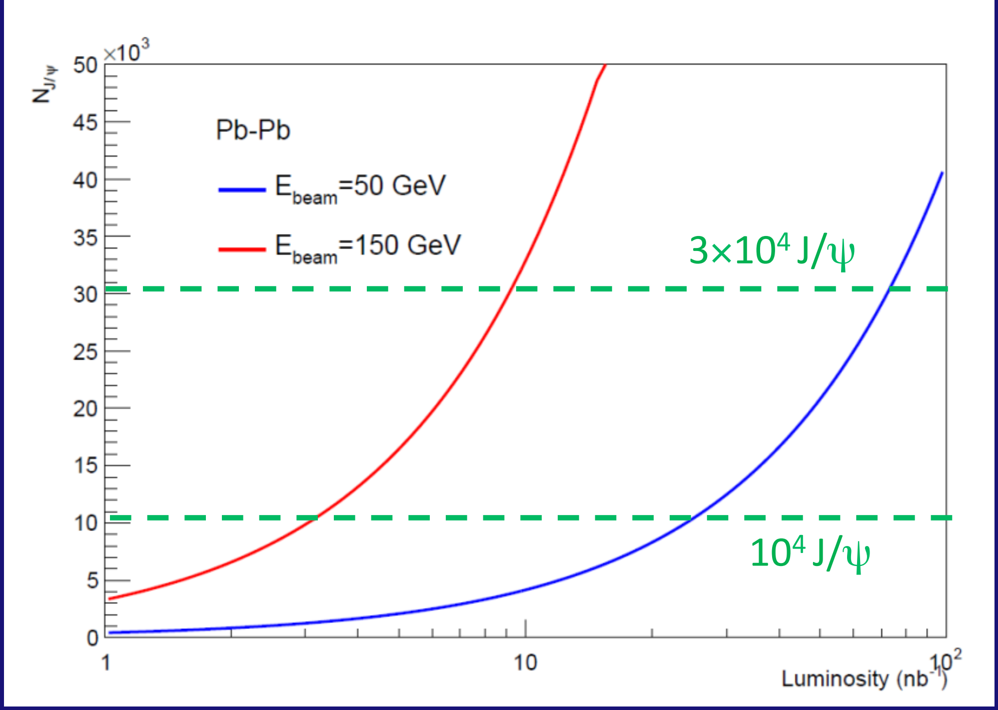
[1] R. Rapp, private discussion

Charmonium production rates

R.Nelson et al., PRC 87, 014908

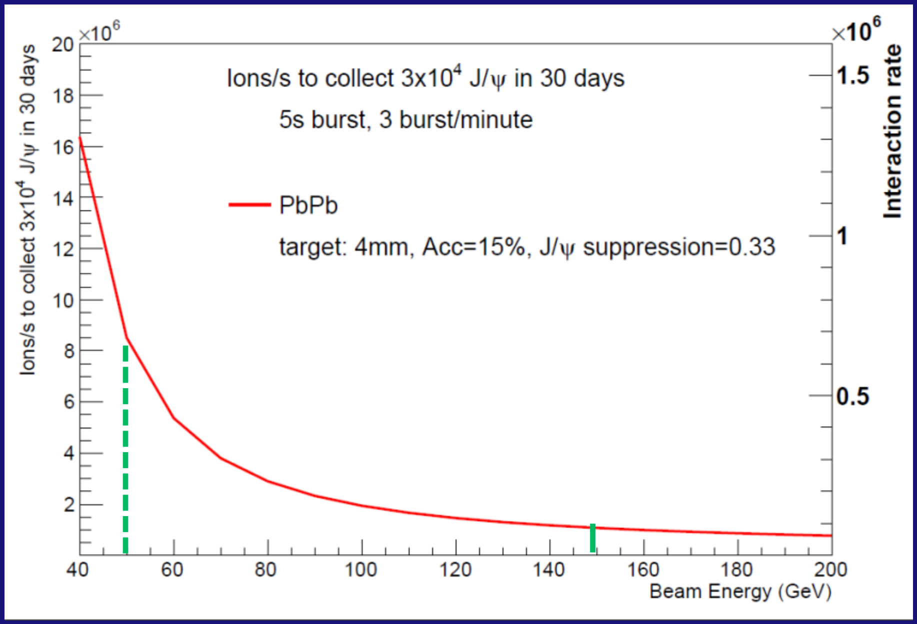


- Few elementary collision data exist for $\sqrt{s}$ < 20 GeV
- Evaluate production cross sections via Color Evaporation Model or empirical parameterizations



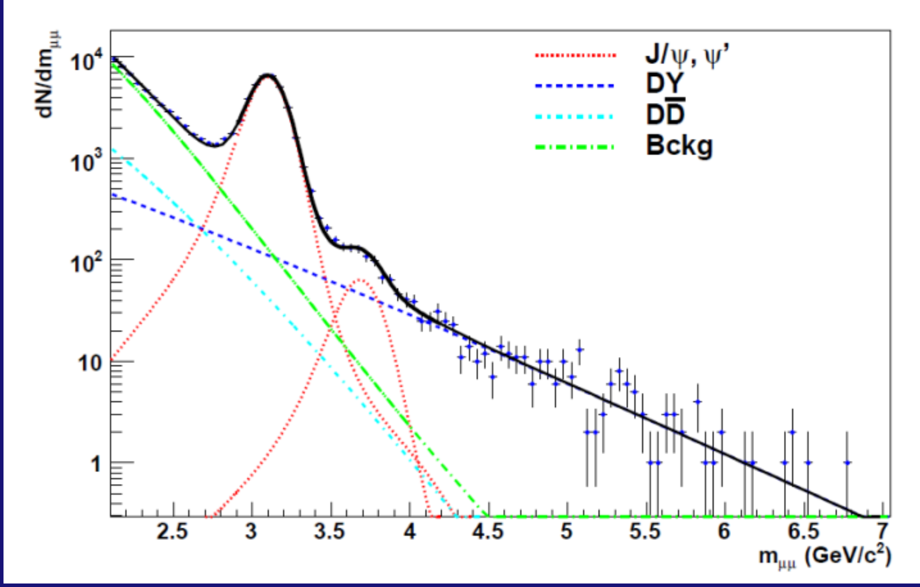
- Expected PbPb statistics vs integrated luminosity
  - 10^4 J/ψ at E_{beam}=50 A GeV L_{int} ~25 nb^{-1}
- Assume:
  - N_{coll} scaling
  - $|y|<0.5$, $|\cos\theta_{CS}|<0.5$
  - A×ε = 0.15
  - 1/3 suppression factor

SPS beam requirements



- Assume 30 days beam time
- Beam intensity ~0.8×10^7 Pb ions/s
  - 3×10^4 reconstructed J/ψ for Pb-Pb collisions at E_{beam} = 50 AGeV

R. Arnaldi et al. (NA60), PRL99 (2007) 132302



- Background levels negligible!
- NA60 (In-In , E_{beam} = 158 A GeV) → J/ψ/(DY+DDbar+comb.)<5%
- Same order of magnitude expected when moving to E_{beam} = 50 A GeV

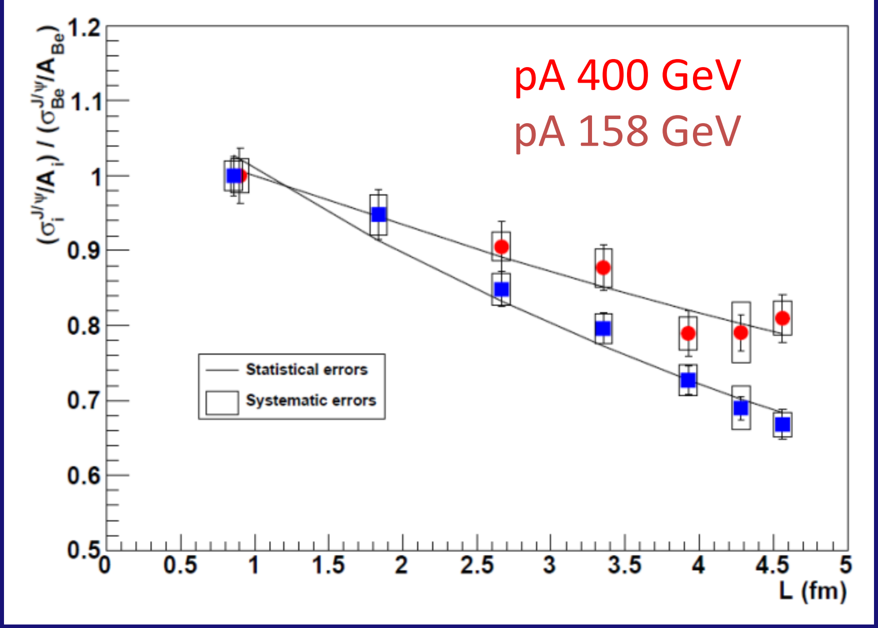
p-A collisions: performance

Measurement of J/ψ production in p-A collisions essential for two main reasons

1) Evaluate $\sigma_{pp}^{J/\psi}$, needed for R_{AA} evaluation, via simple and robust extrapolations (direct use of H_2 target more complicate in fixed-target environment)

$$\sigma_{pA}^{J/\psi} = \sigma_{pp}^{J/\psi} A^{\alpha}$$

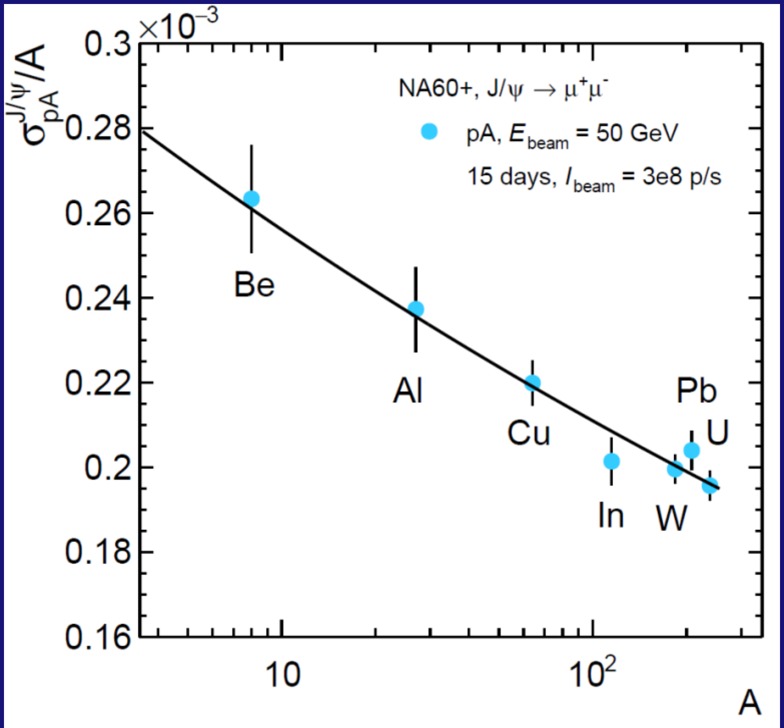
2) Evaluate shadowing/break-up effects in cold nuclear matter, which were shown (NA60) to become important when collision energy decreases



NA60, PLB 706 (2012) 263

p-A collisions: NA60+ performance

- Measurement with 7 1 mm thick nuclear targets
- Simultaneously exposed to the beam, as done in NA60 (Be, Al, Cu, In, W, Pb, U)
- Assume a J/ψ absorption cross section in CNM $\sigma_{abs}^{J/\psi}$= 4.3 mb
- ≈15 days of proton beam time, I=3 10^8 s^{-1} (with SPS burst structure) and E = 50 GeV



Use this plot to

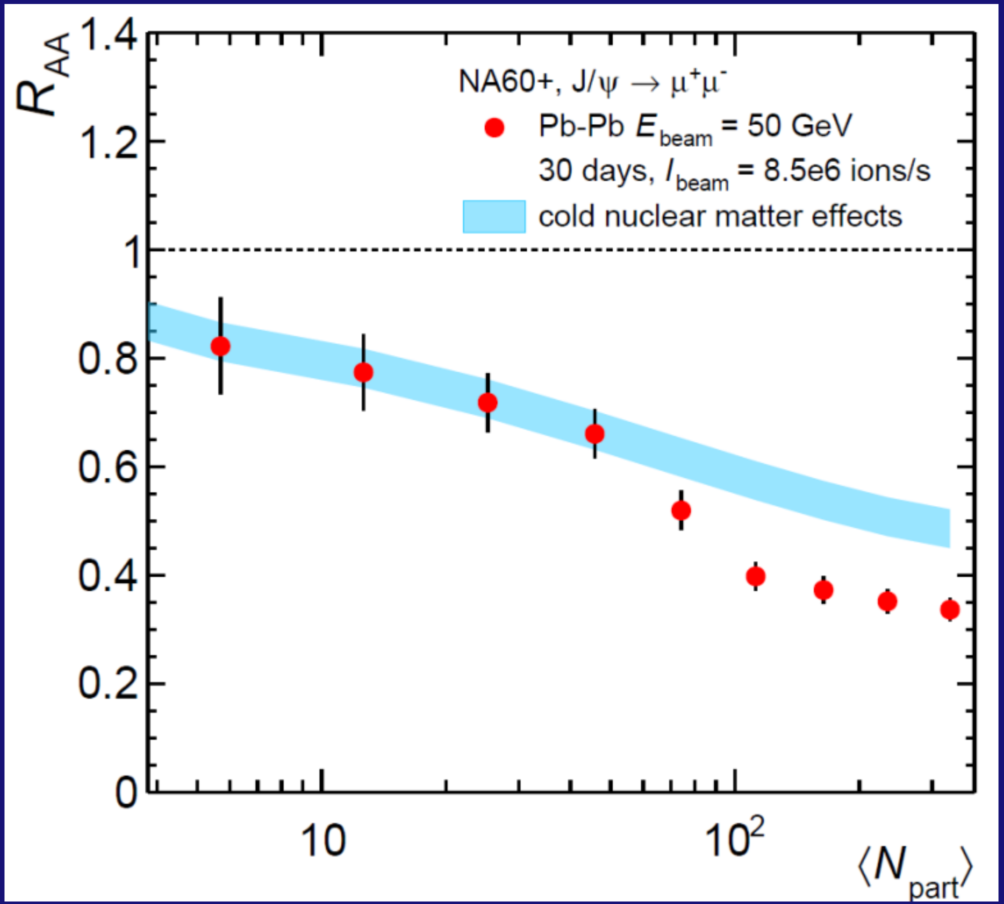
1) Extrapolate to $\sigma_{pp}^{J/\psi}$
2) Estimate the uncertainty on $\sigma_{abs}^{J/\psi}$

Physics performance : R_{AA}

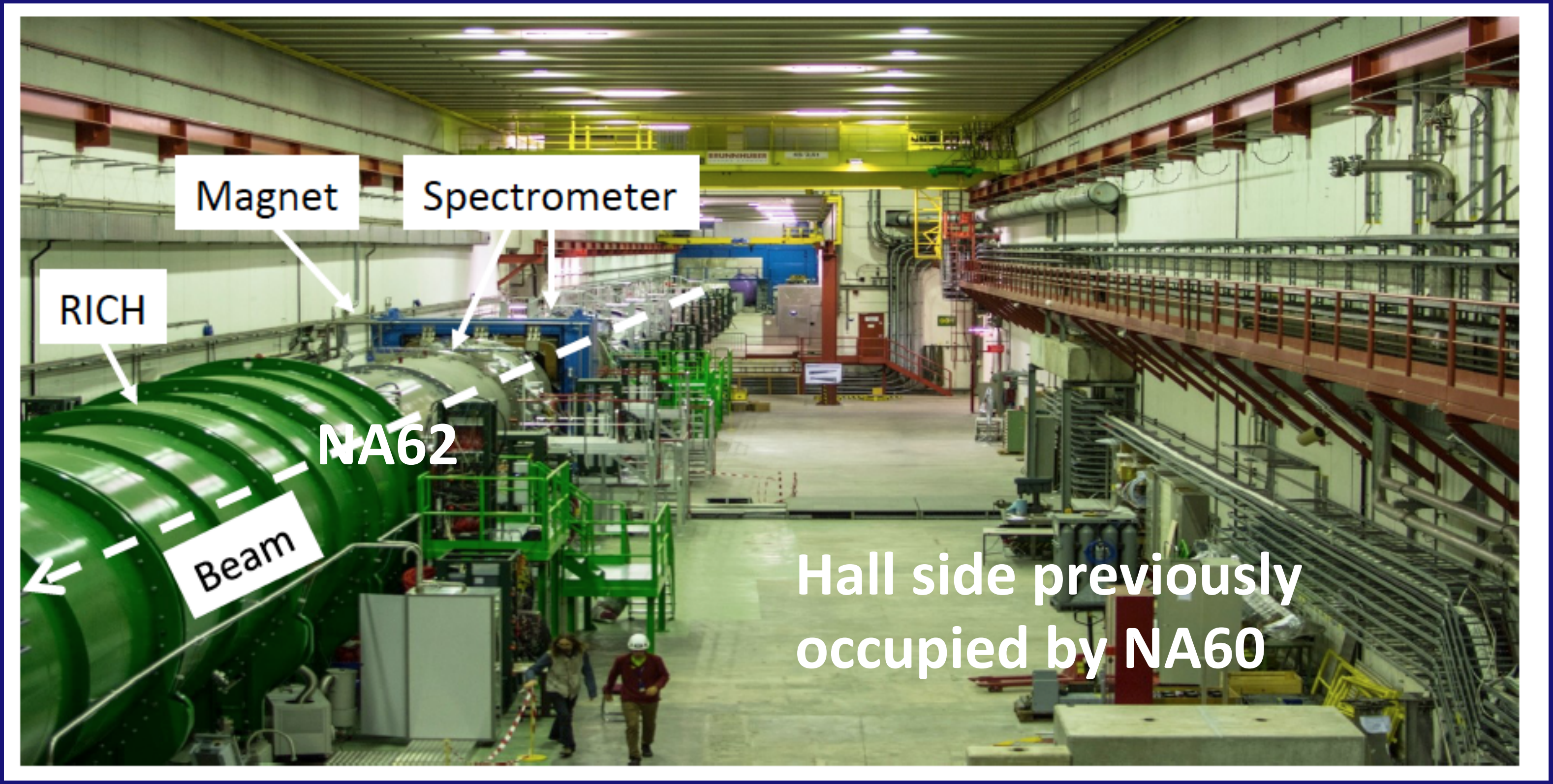
- Assumption on observed J/ψ suppression:
  - due to CNM effects up to $N_{part} \sim 50$
  - Then anomalous suppression giving a 20% extra suppression

30 days Pb beam time at
I = 8.5 10^6 Pb/s (4mm Pb tgt)
AND
a pA data taking like the one detailed before

Even at low SPS energy an accurate estimate of R_{AA} can be carried out and an anomalous suppression be detected



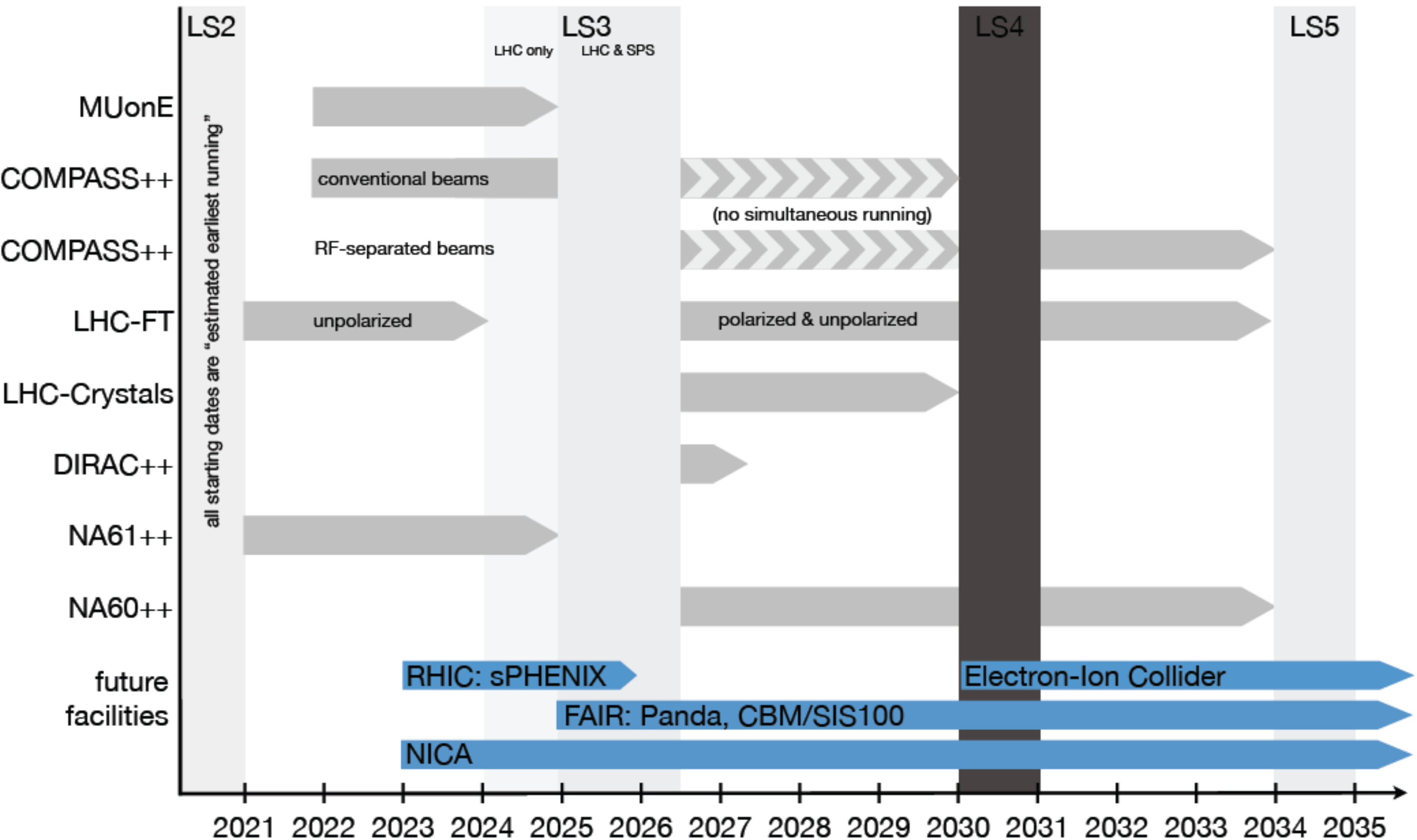
Installation site, timeline



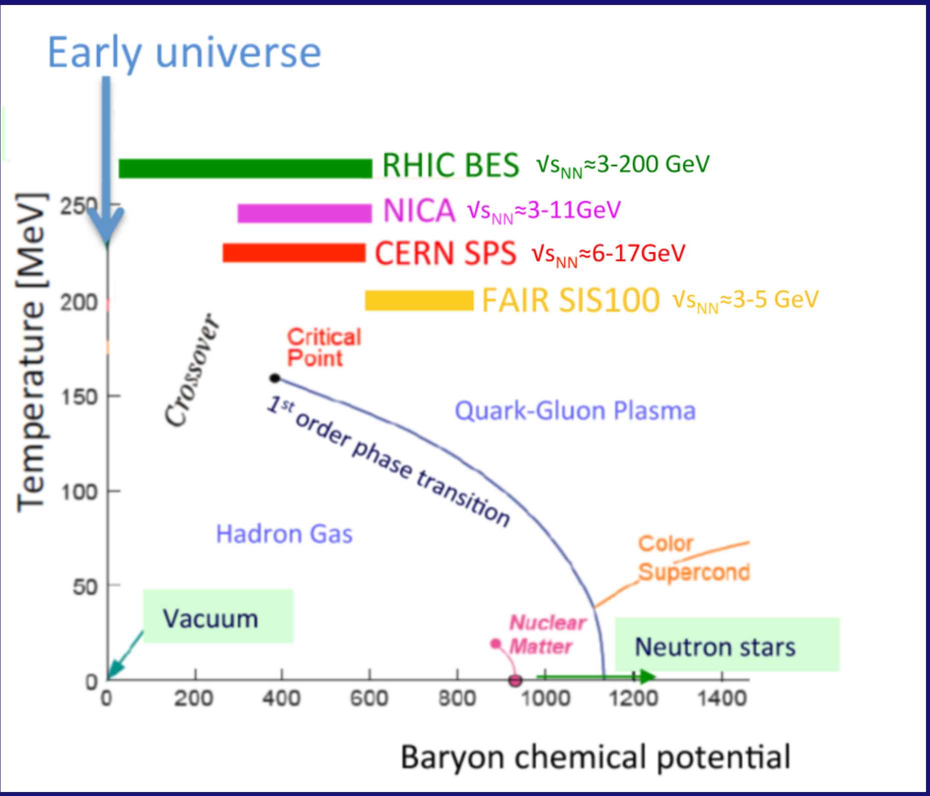
- Required beam intensity: installation possible only in ECN3 underground
- Project under discussion together with NA62/KLever and Dirac+ proposals after LS3 for run4 within CERN Physics Beyond Colliders

Timeline

Timeline table of different proposal discussed within Physics Beyond Colliders (QCD working group)



Competitiveness of NA60+/CERN SPS in the landscape of existing or future facilities



CERN SPS : large μ_B coverage -high interaction rates (>1 MHz)

GSI SIS100 : complementary μ_B region -high interaction rates (>1 MHz)

Collider facilities (NICA, RHIC): large μ_B coverage - interaction rates lower by 2-3 orders of magnitude
Also RHIC fixed target program not competitive for high precision dilepton measurements

- NA60+ - CERN SPS:
  - Optimal combination of wide μ_B coverage of phase diagram and large interaction rates

Outlook

- Project discussed within Physics Beyond Colliders
  - Expected to produce a document by the end of this year to serve as an input for the European Particle Physics Strategy

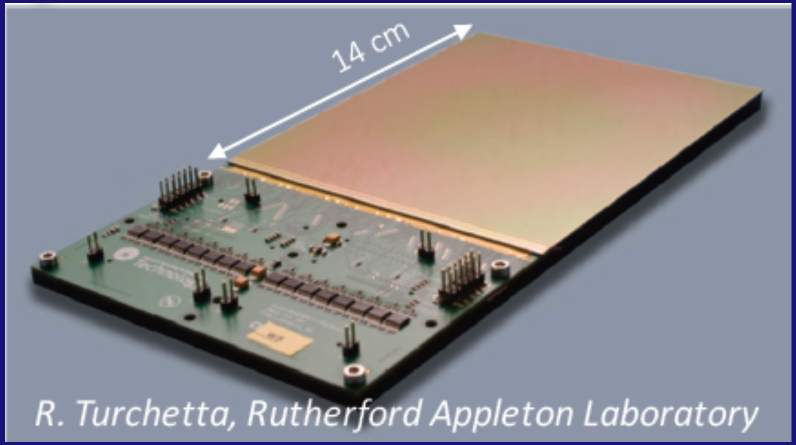
- Working group from several institutions working on the preparation of a Letter of Intent to be finalized by end of the year:
  - Cagliari (INFN), Kolkata (Saha institute), Lyon (IPNL), Munich (TUM), Padova (INFN), Rice University, Stony Brook University, Tohoku University (Japan), Torino (INFN)

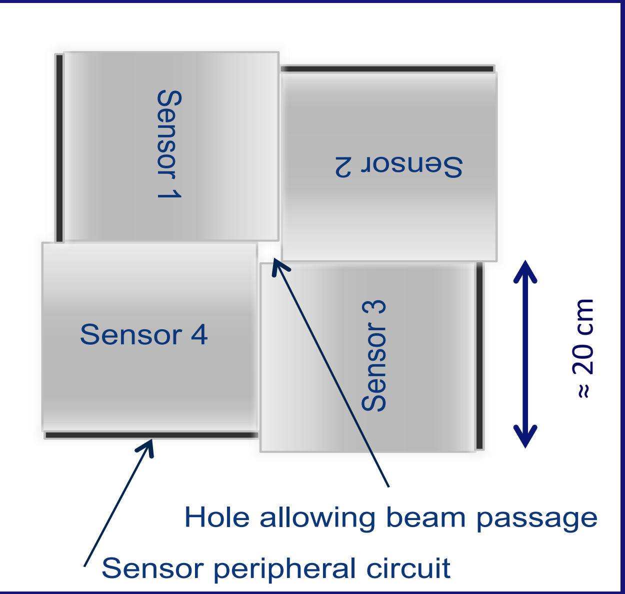
- We invite interested people to contact us (na60-plus@cern.ch)

backup

Detectors for silicon tracker

- State of the art monolithic pixels with stitching →possible sinergy with ALICE upgrade after LS3. Meet requirements in terms of:
  - very large area (wafer size), material budget (0.1% X_0), resolution (5 μm)
  - rate/cm^2 (max 50-100 MHz/cm^2) but optimization of readout band-width required





Example of pixel plane with just 4 ≈ 20x20 cm^2 sensors with total material budget of 0.1% X_0!

- State of the art hybrid pixels: →CMS/ATLAS development for HL-LHC after LS3 might be also a very good option. Compared to monolithic pixels:
  - very fast, very high radiation resistant
  - worse material budget and space resolution, more complex integration

The STAR BES at RHIC for comparison

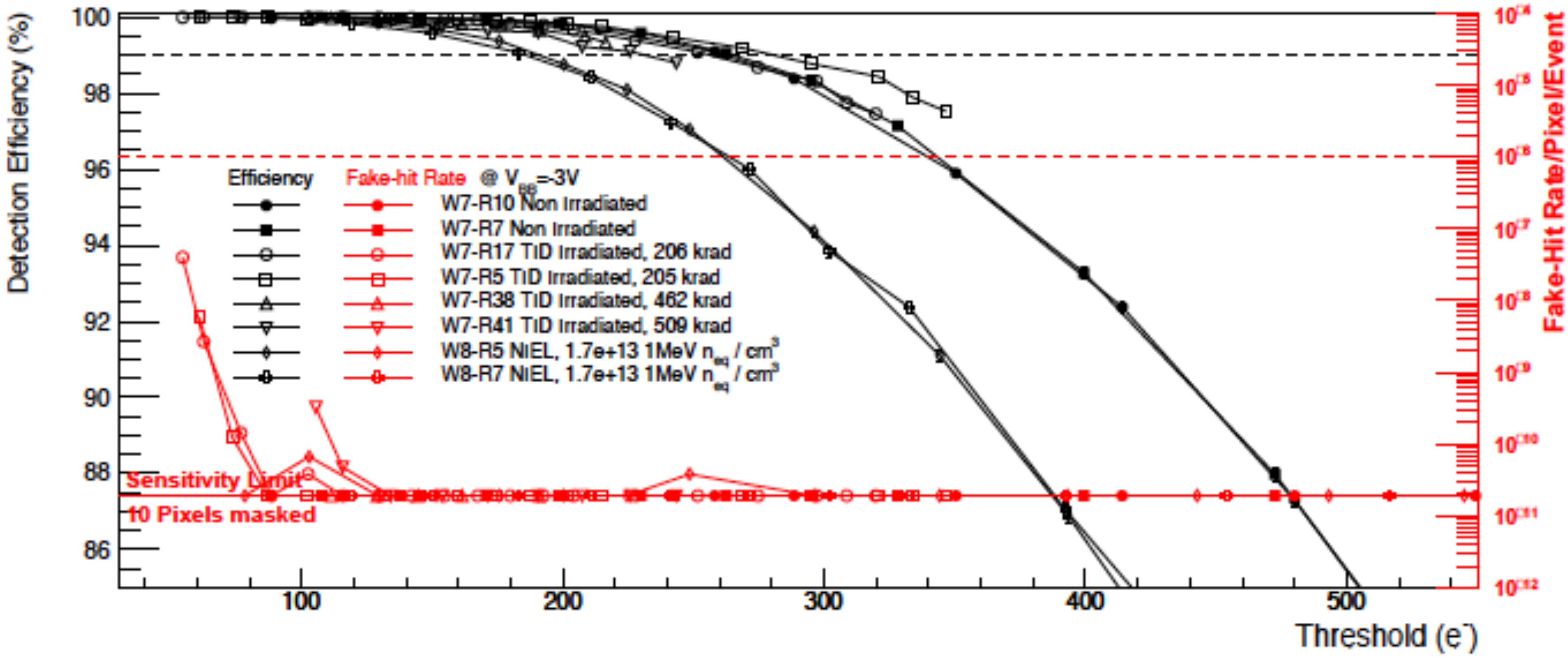
- BES II goal: statistics ranging from 400×10^6 mbias events ($\sqrt{s}$ = 19.6 GeV) to 100×10^6 mbias events ($\sqrt{s}$ = 7.7 GeV)
- STAR fixed target : energy range to be extended further down to $\sqrt{s}$ = 3 GeV
  Statistics goal: 10^8 mbias events/energy (same sensitivity as BES-II)

STAR - QM2017

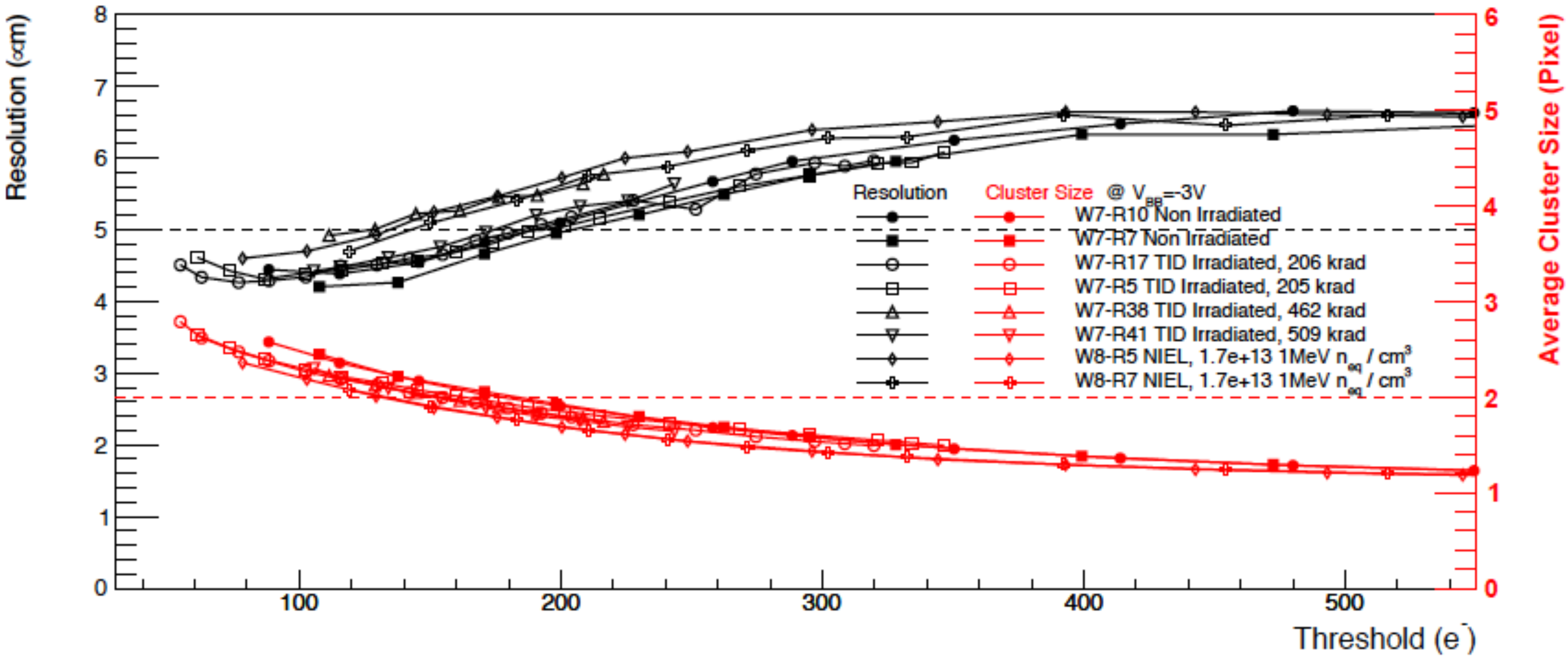
Collision Energy (GeV)	BES-II Proposed Events Goal (M)	BES-I Events (M)
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36

In 2003 NA60 at $\sqrt{s}$=17.3 GeV collected >200×10^6 triggered muon pairs. This means that BESII will not be able to reach even the precision of the former NA60 in dilepton measurements

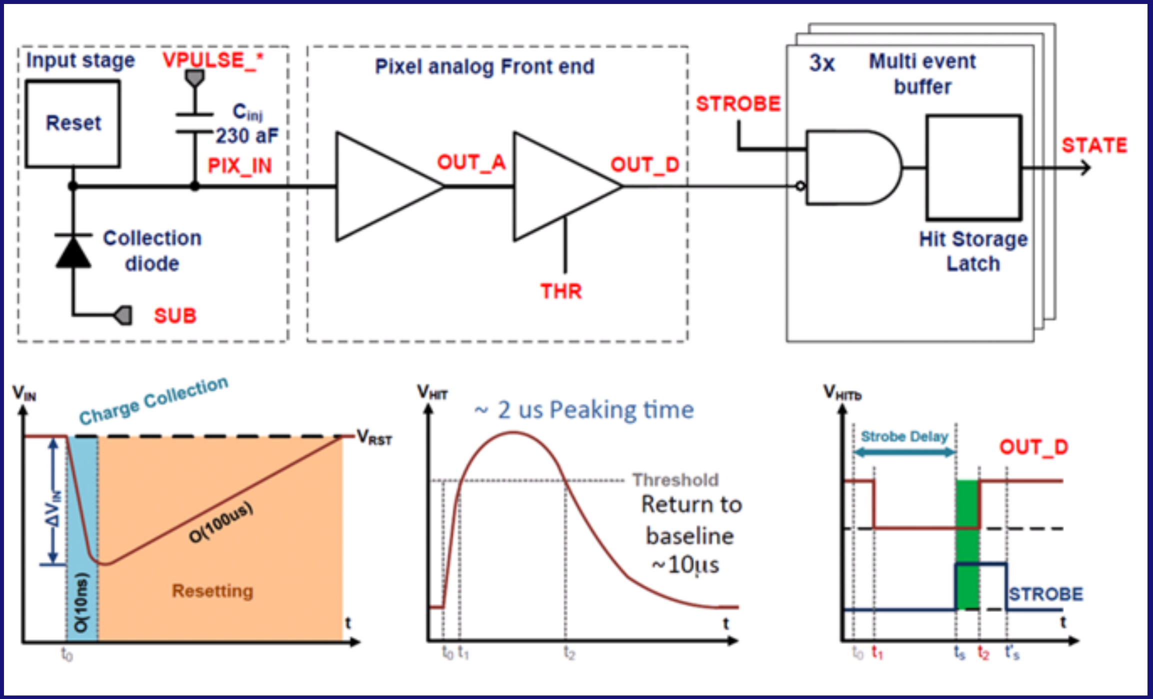
Detection efficiency and fake hit rate



Position resolution and pixel cluster size



High rate operation (int rate > 1 MHz)



Continuous mode: readout of pixel hits sampled during periodically repeating strobing intervals, with a duration equal to the interval between two consecutive ones.

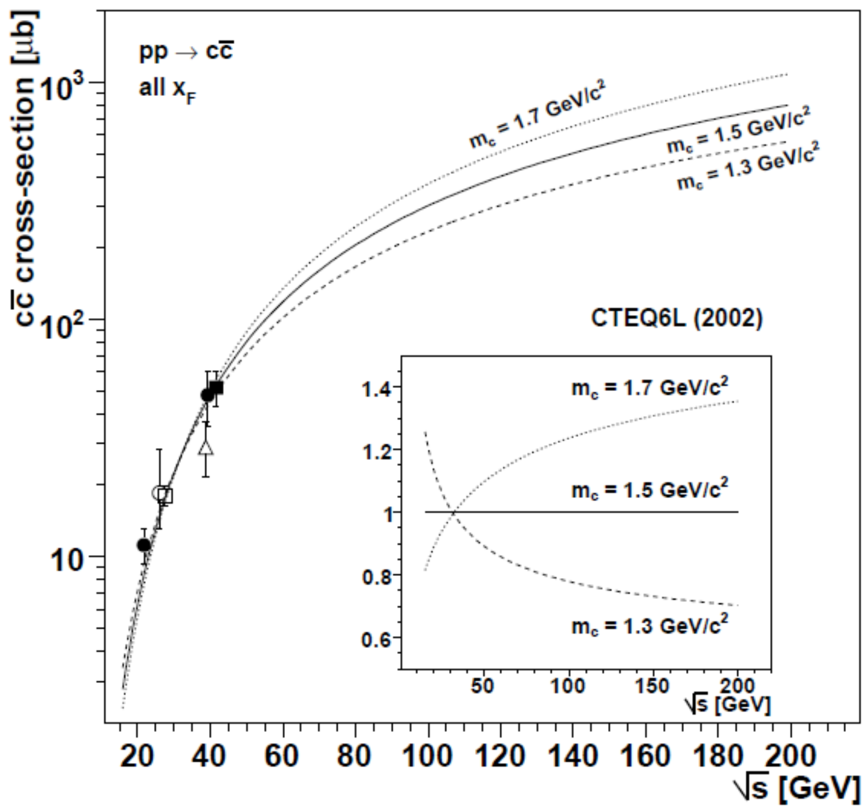
Framing intervals should be few hundred ns: strobe duration O(100 ns), strobe gaps O(100 ns)

Issue: chip prioritises newly received frame requests over data that are already stored within the matrix

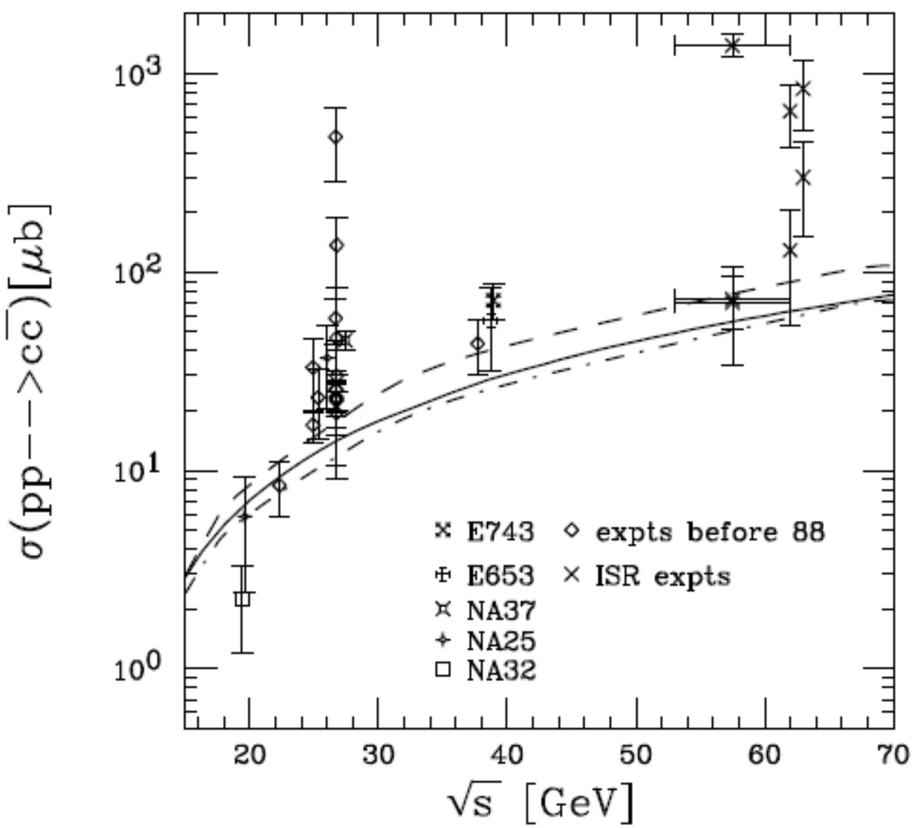
Charm cross section in pp/p-A

Measurements in the SPS energy domain vs. pQCD

PYTHIA LO cross sections scaled with appropriate K-factor

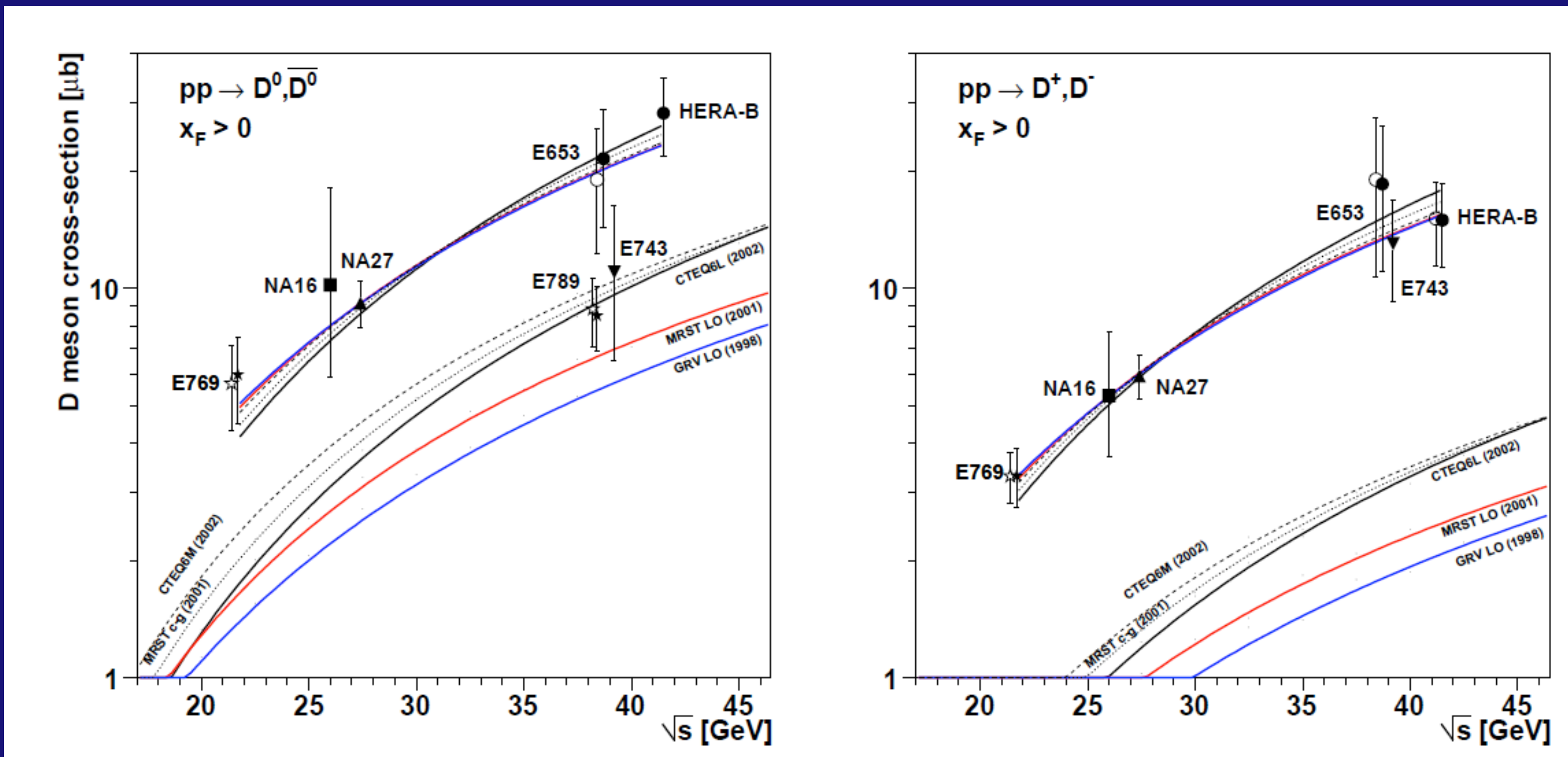


MNR calculations with m_c=1.2 GeV and μ=2m_c



Charm cross section in pp/p-A

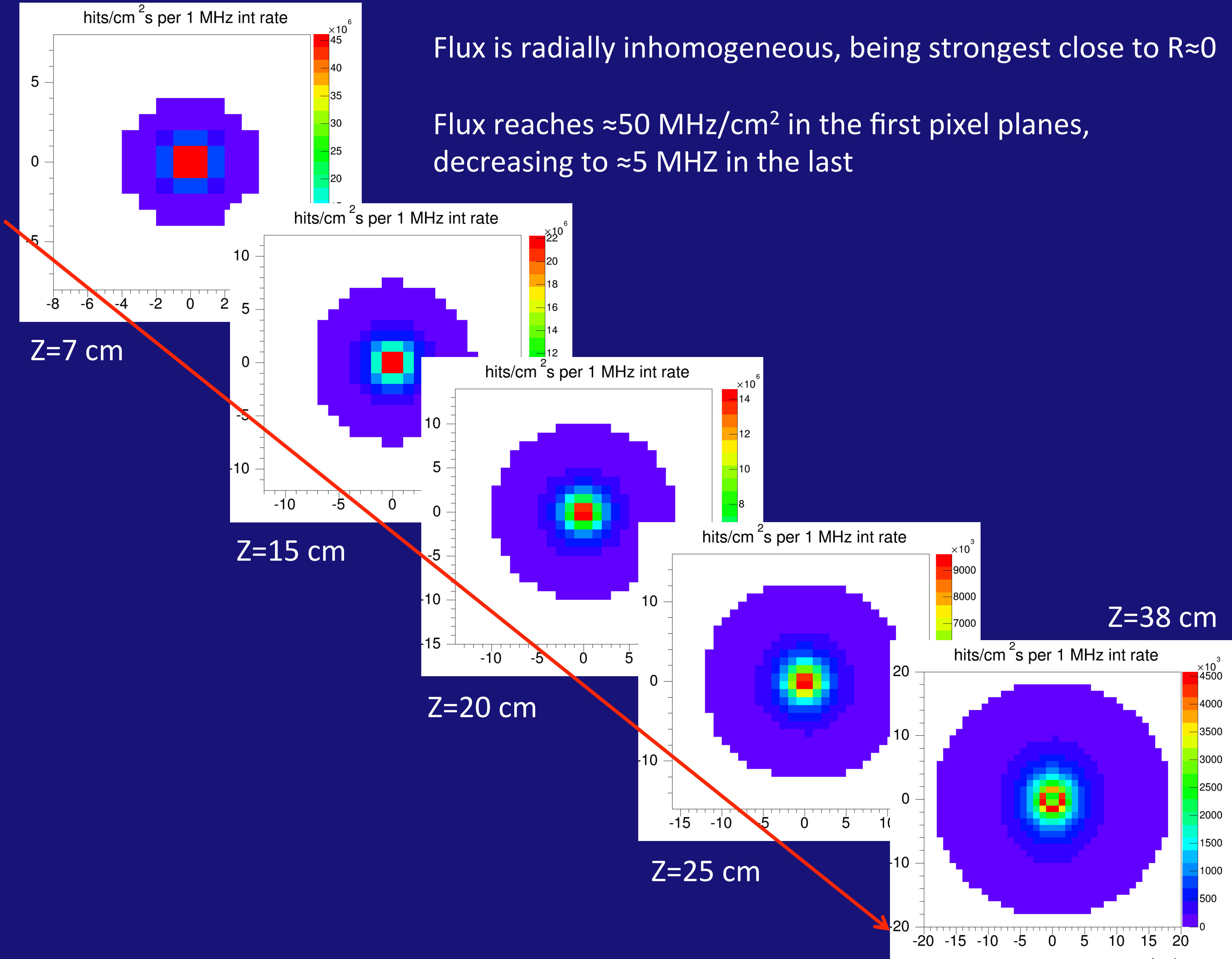
- Measurements in the SPS energy domain vs. PYTHIA



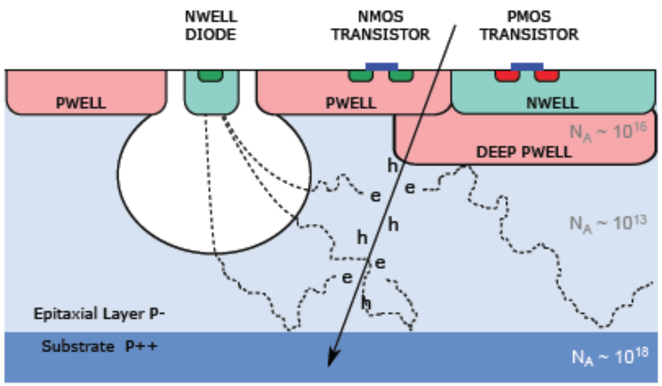
C. Lourenco, H. Wohri, arXiv:hep-ph/0609101

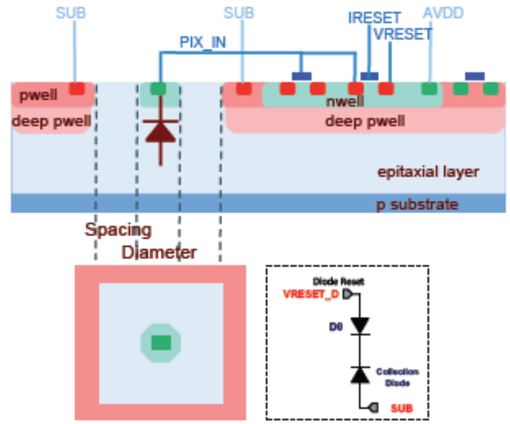
Flux is radially inhomogeneous, being strongest close to R≈0

Flux reaches ≈50 MHz/cm^2 in the first pixel planes, decreasing to ≈5 MHZ in the last



MAPS state of the art: ALICE ALPIDE



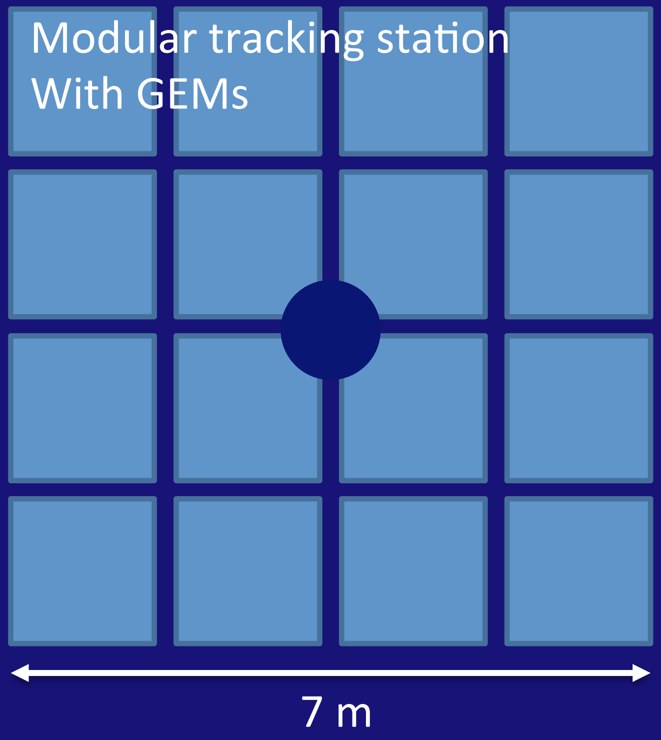


CMOS Pixel Sensor - TowerJazz 0.18μm CMOS Imaging Process

- High-resistivity (> 1kW cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors (full CMOS circuitry within active area)

Detectors for muon tracking and trigger

- Gem detectors meet fully the requirements for the muon tracking:
  - Fine patterning realized with PCB photolithography techniques
  - position resolution (~100-200 μm)
  - Good timing resolution (< 10 ns)
  - rate capability (max 10 KHz/cm^2)
  - Excellent radiation hardness
  - Use components that can be mass produced by industry



- RPC detectors similar to ALICE meet fully the requirements for the muon trigger in terms of:
  - Ageing
  - Rate capability (max 100 Hz/cm^2)

High-mass background at low SPS energy

	From E_{beam} = 150 to 50 GeV
J/ψ ($\sqrt{s}$ parameterization)	~7.2
Drell-Yan (Pythia, LO), $\|y\|< 0.5$, $2.9<m_{\mu\mu}<3.3$ GeV/c^2	~5
$DD \rightarrow \mu\mu$	$\sim 10^2$ (as $\sigma_{cc}{}^2$)
Combinatorial background (pion, kaon decays)	~4 (as $dN_{ch}/d\eta^2$)

Conclusion

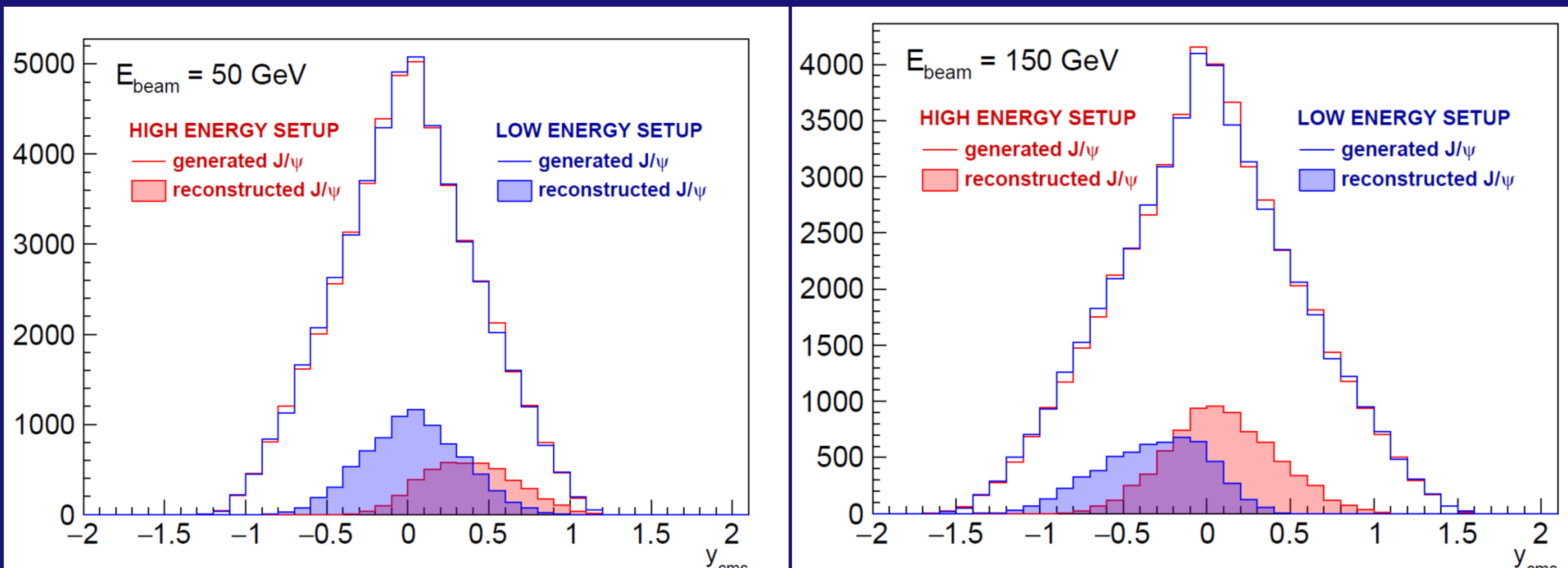
1) All expected sources decrease by the same order of magnitude

2) DD likely to become negligible

Study of J/ψ acceptance

Acceptance studies

Follow the shift of center-of-mass rapidity vs collision energy



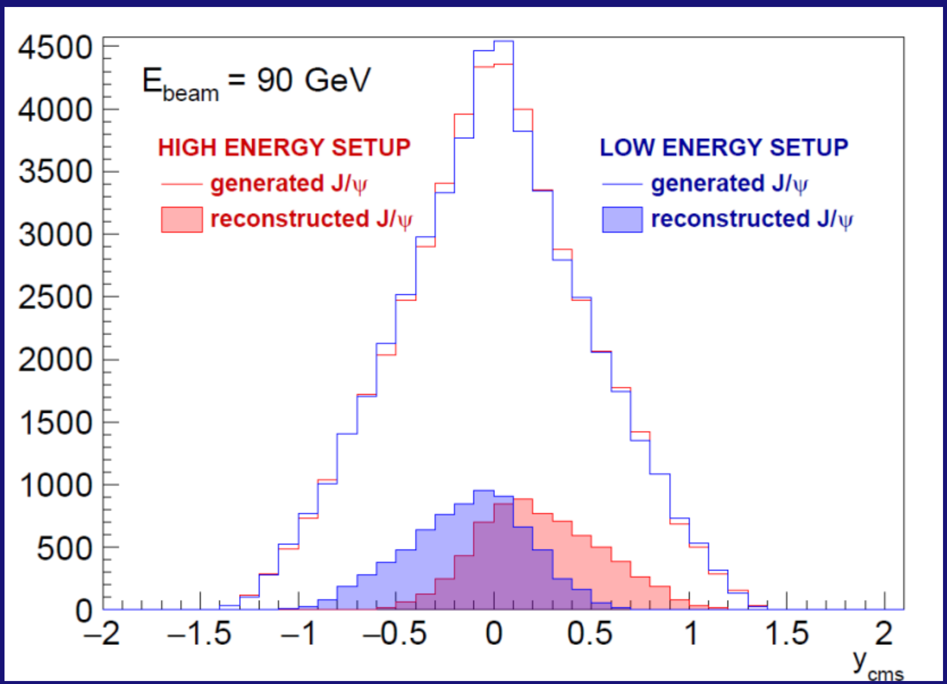
With the two "default" set-ups the coverage is optimized (by definition!) at the two edges of the energy scan

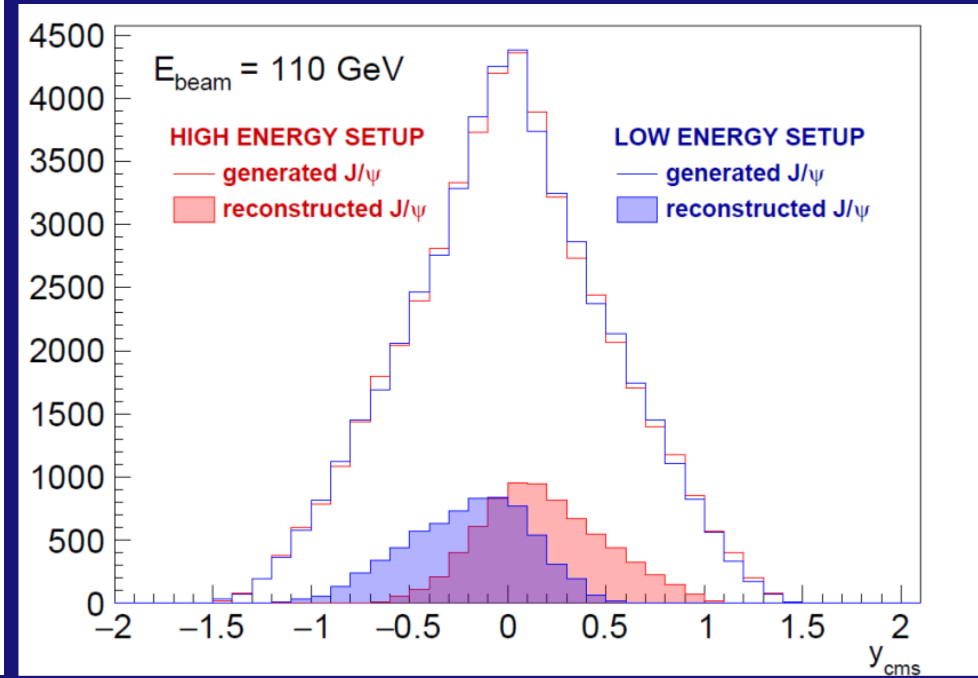
What about "intermediate" energies ?

Study of J/ψ acceptance

Acceptance studies

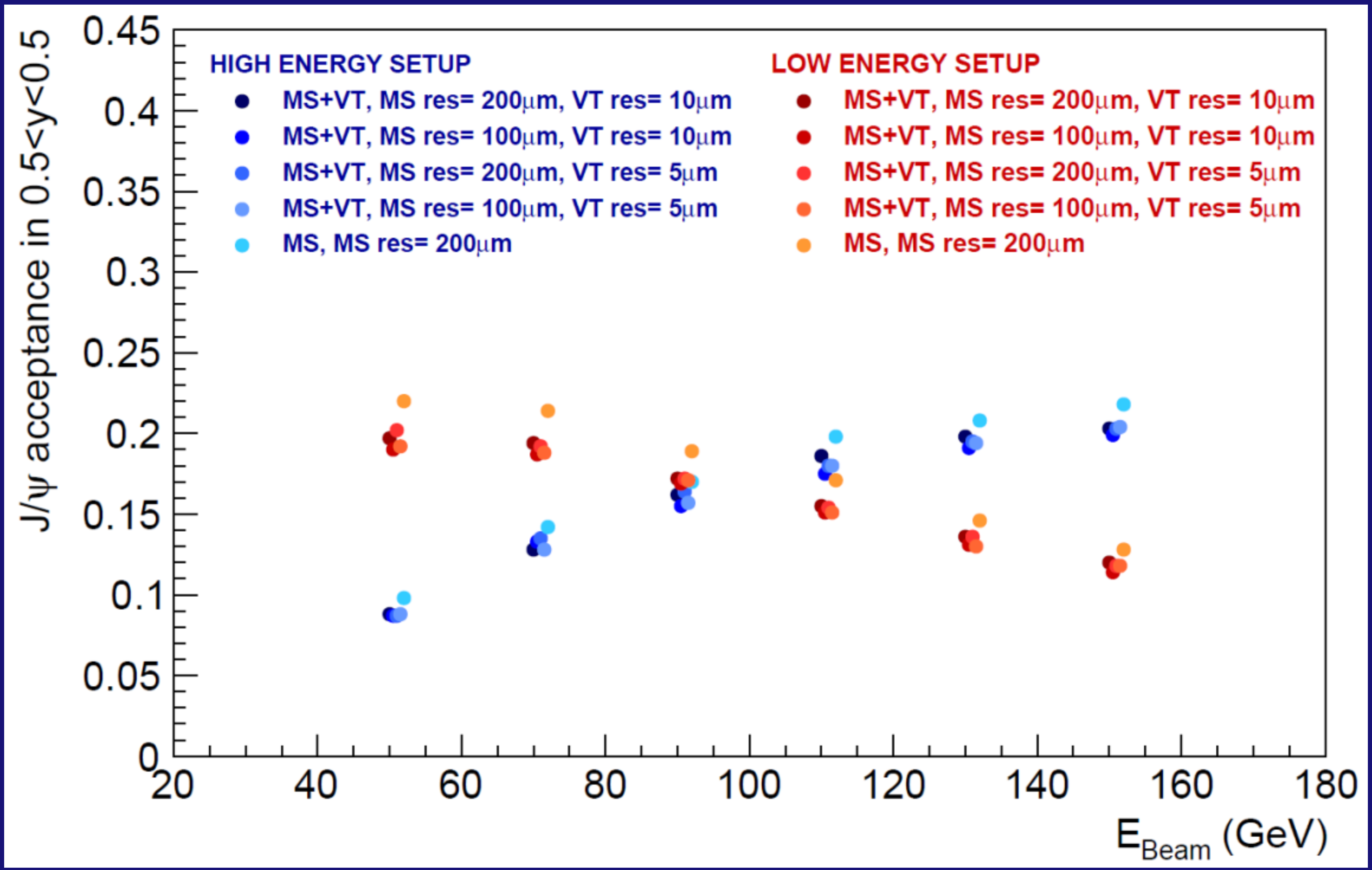
Follow the shift of center-of-mass rapidity vs collision energy





Coverage still reasonable in 1 unit of rapidity around y=0

Study of J/ψ acceptance

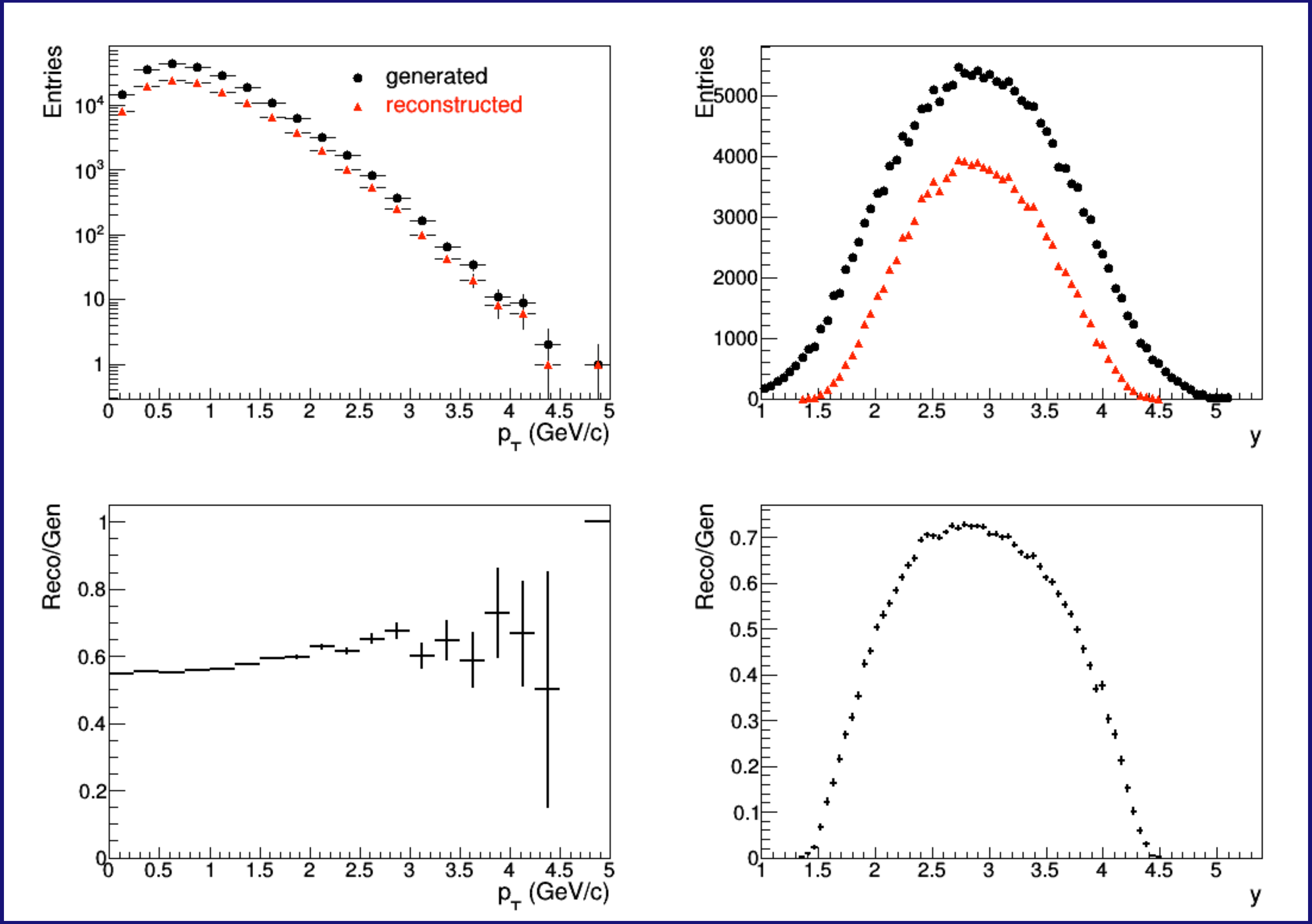


In the fiducial region |y|<0.5, acceptances between 15 and 20%, using the appropriate set-up (low or high energy)

Modest dependence (as expected) on detector resolutions

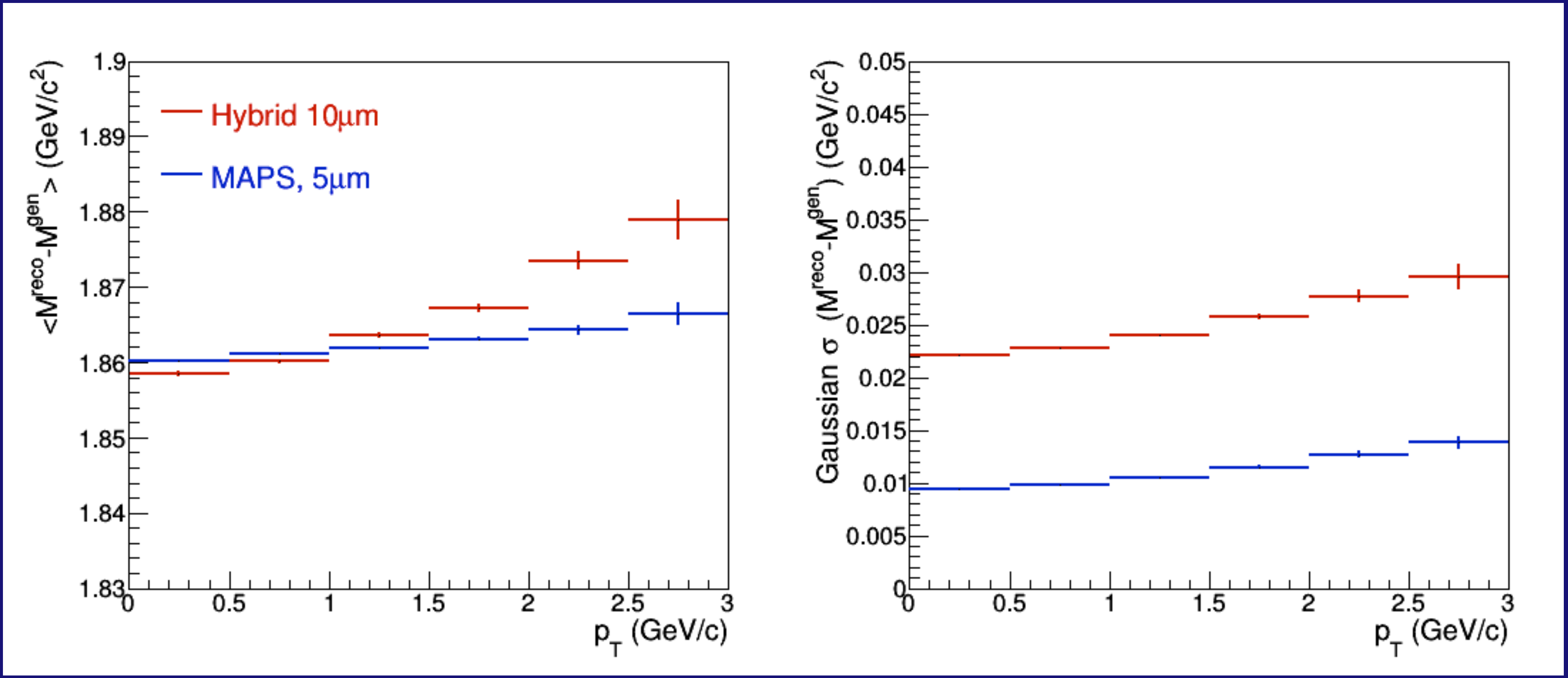
Signal simulation: efficiency

- D^0- acceptance x reconstruction efficiency
  - Similar for the two pixel configuration

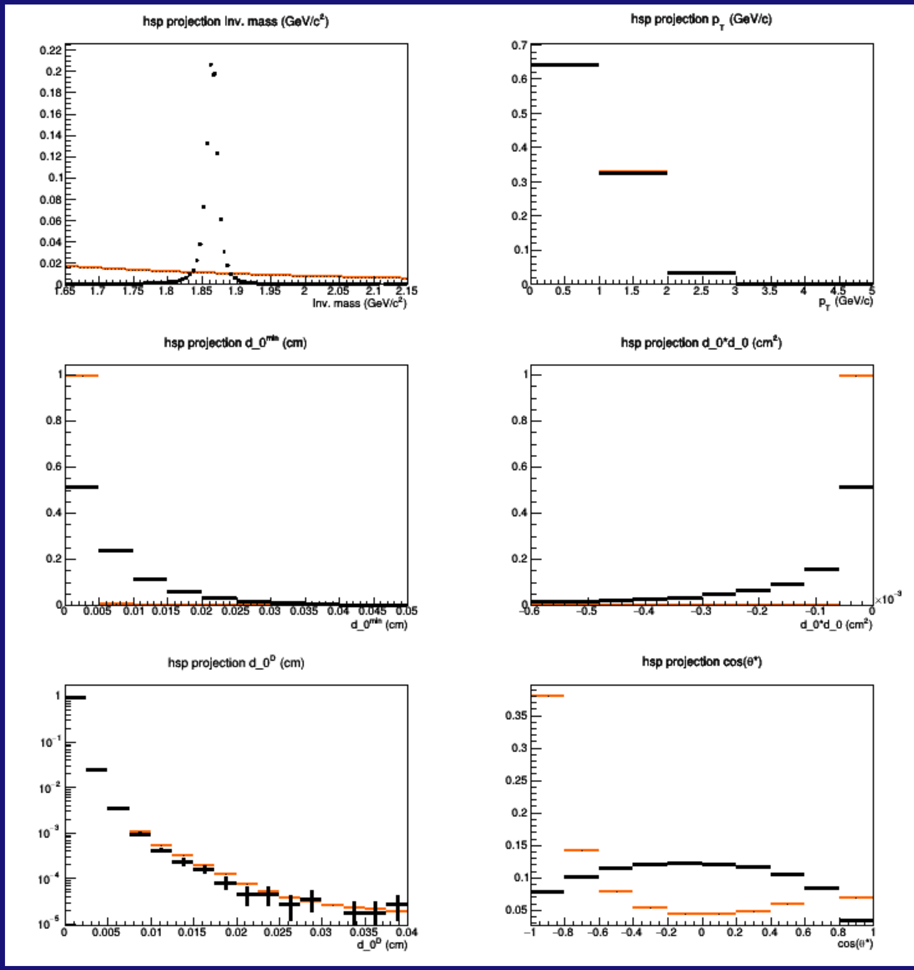


D^0 simulation: mass resolution

- D^0 invariant mass resolution



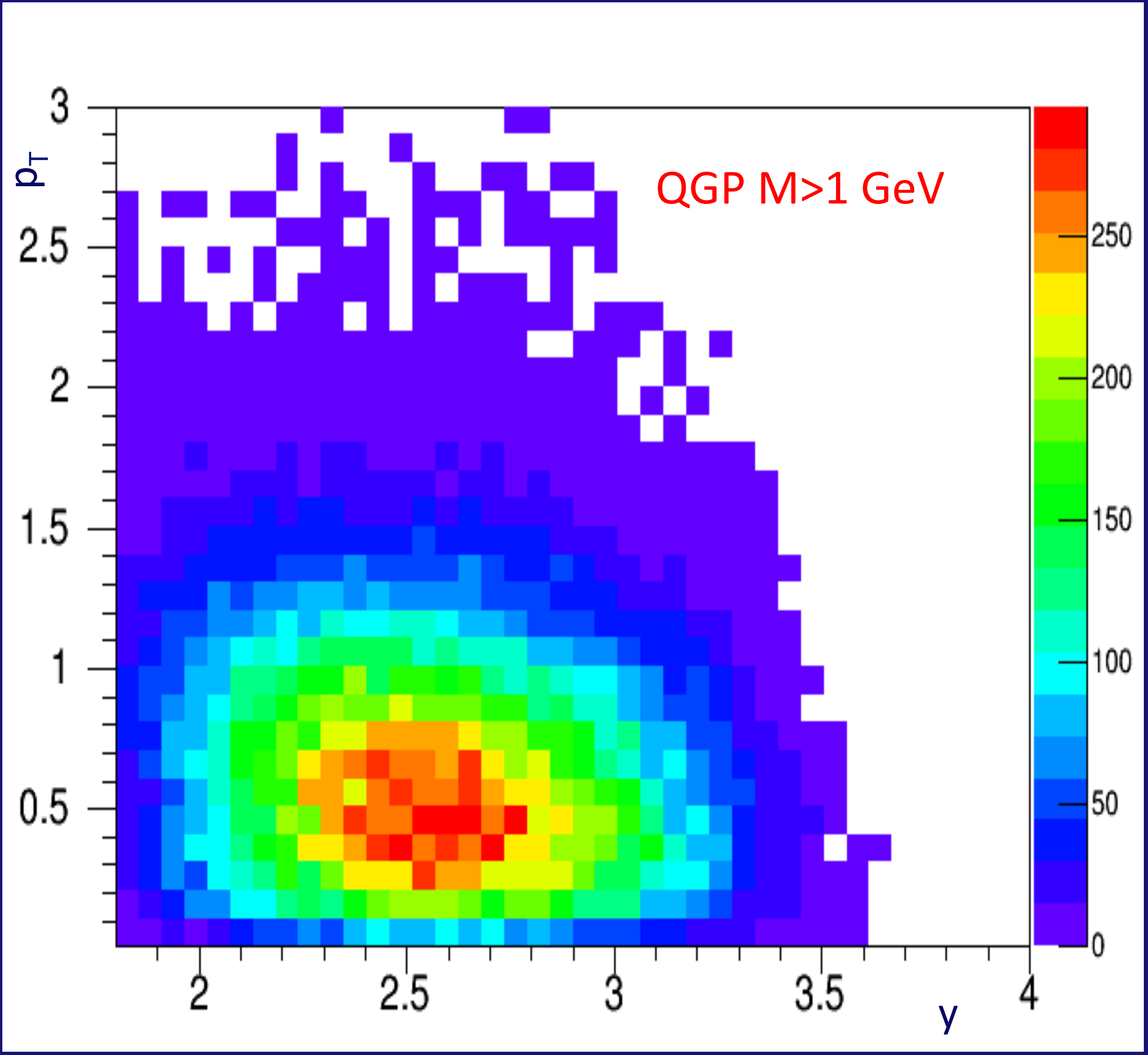
Cut variables (MAPS 5 µm setup)



Signal

Background

p_T vs y coverage



Extrapolation of CNM effects

At SPS energies CNM effects were shown to scale in such a way that

$\sigma_{pA}^{J/\psi} = \sigma_{pp}^{J/\psi} \exp(-\rho\, \sigma_{abs}^{J/\psi} L)$

L = thickness of nuclear matter crossed by the ccbar pair (calculated via Glauber model)

L calculated for Pb-Pb collisions as a function of centrality (Glauber) and the size of CNM effects are evalauted