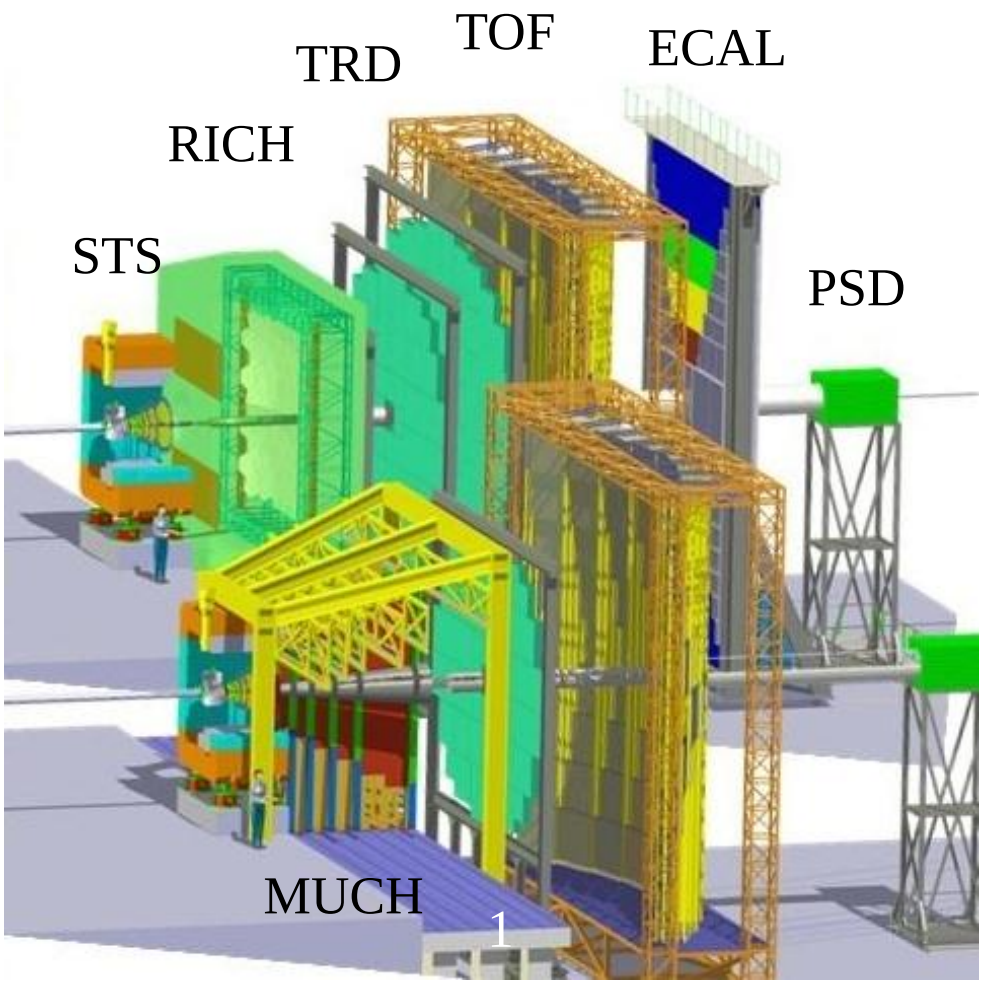
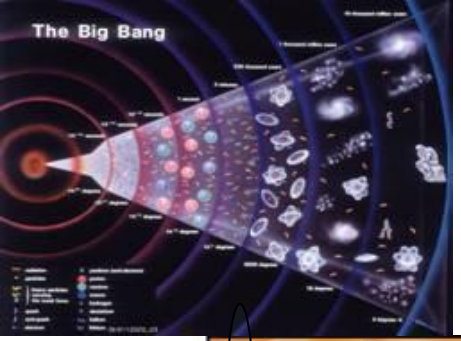
The CBM heavy-quark program

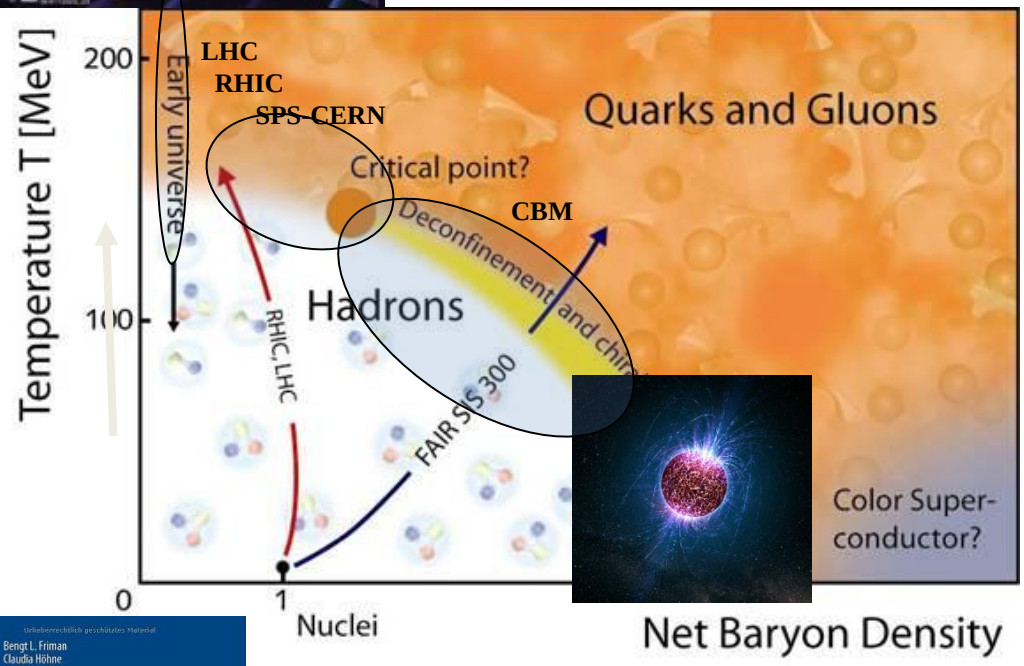
5th International workshop on heavy quark production in heavy-ion collisions

Vassiliev Iouri , CBM Collaboration



Physics case:
Exploring the QCD phase diagram





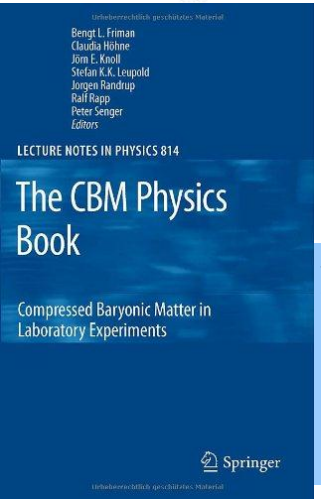
The equation-of-state at high ρ_B
- collective flow of hadrons
- particle production at threshold energies (**open charm**)

Deconfinement phase transition at high ρ_B
- excitation function and flow of strangeness (**K, Λ, Σ, Ξ, Ω**)
- excitation function and flow of **charm** (**J/ψ, ψ', D^0, D_s, $D^\pm$, Λ_c**)
- **charmonium** suppression, for **J/ψ** and **ψ'**

QCD critical endpoint
- excitation function of event-by-event fluctuations (K/π,...)

Onset of chiral symmetry restoration at high ρ_B
- in-medium modifications of hadrons

($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$, D?, Σ^*?)



Projects to explore the QCD phase diagram at large μ_B:

RHIC energy-scan, NA61@SPS, MPD@NICA bulk observables

CBM@FAIR/SIS-300 bulk and **rare observables, high statistic!**

Experiments on superdense nuclear matter
Why CBM?

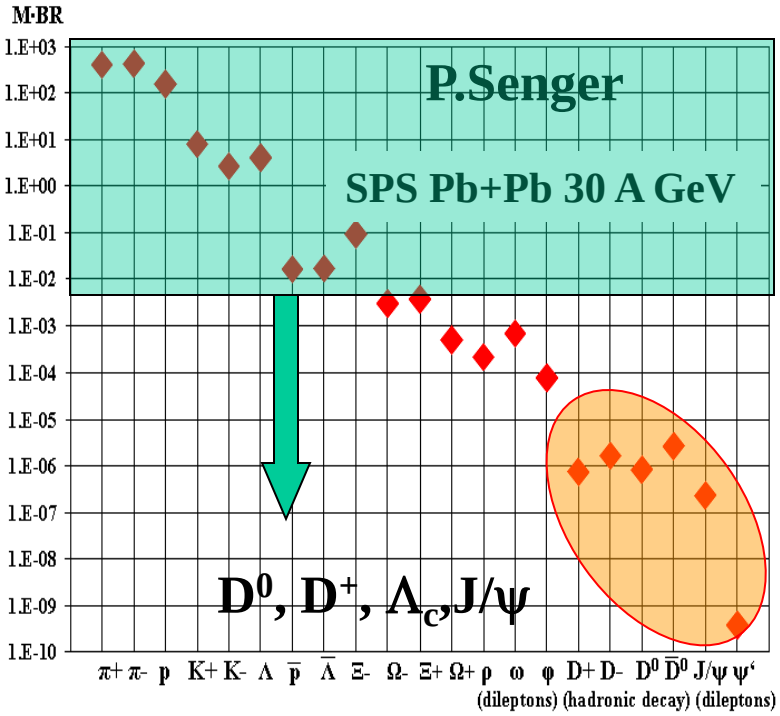
Experiment	Energy range (Au/Pb beams)	Reaction rates Hz
STAR@RHIC BNL	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1 – 800 (limitation by luminosity)
NA61@SPS CERN	E_{kin}= 20 – 160 A GeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limitation by detector)
MPD@NICA Dubna	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (design luminosity of 10^{27} $cm^{-2}s^{-1}$ for heavy ions)
CBM@FAIR Darmstadt	E_{kin}= 2.0 – 35 A GeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV	**10^5 – 10^7** (limitation by detector)

The mission:

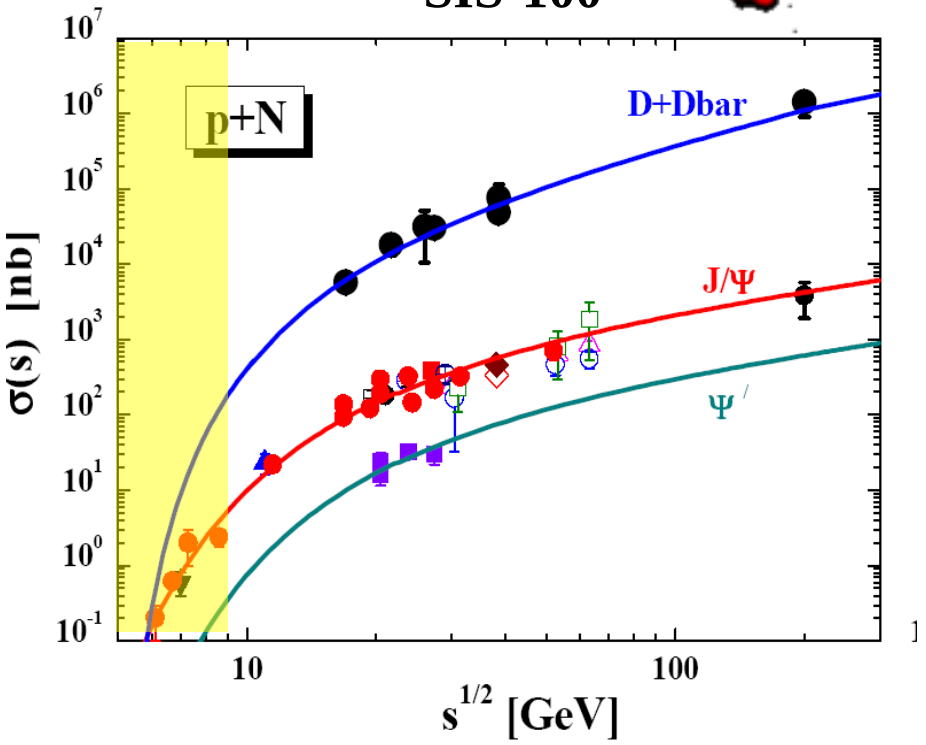
$D^0, D^+, D_s^+, \Lambda_c, D^*$

$J/\psi, \Psi'$

SIS-300

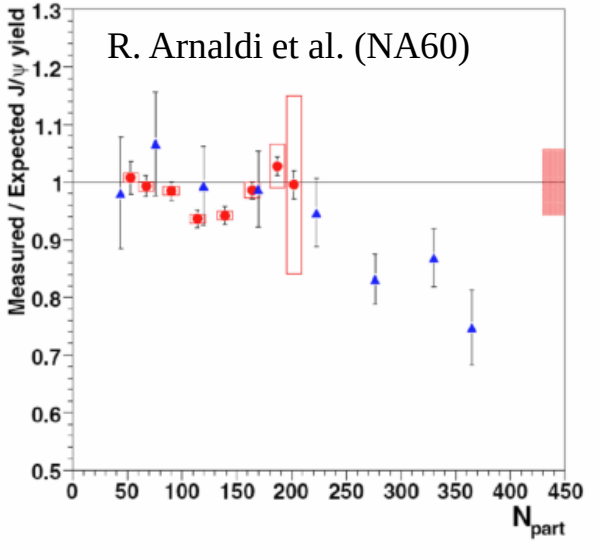


SIS-100

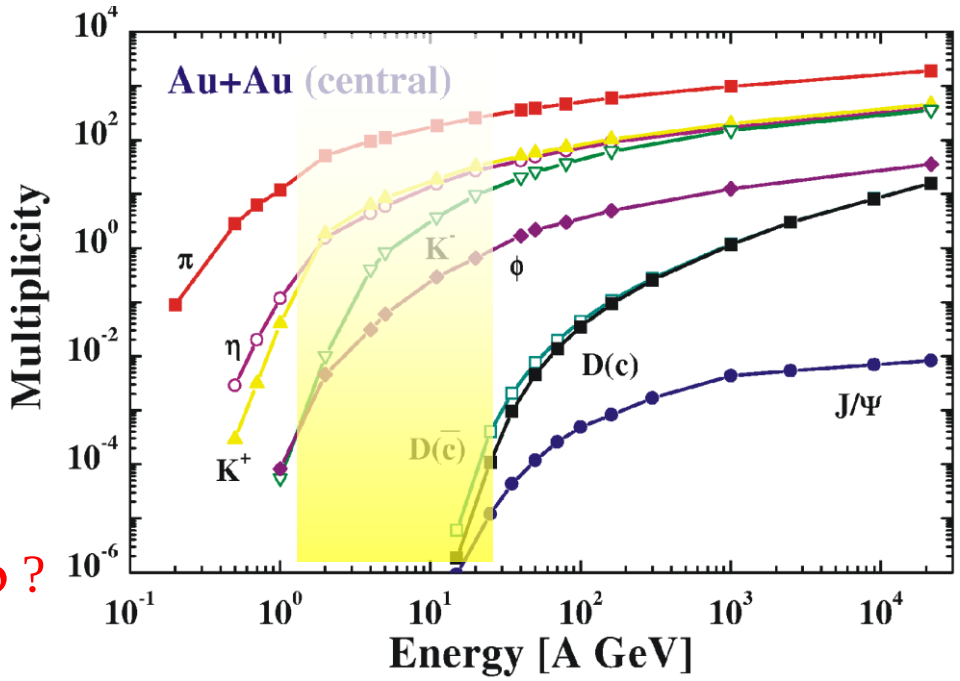


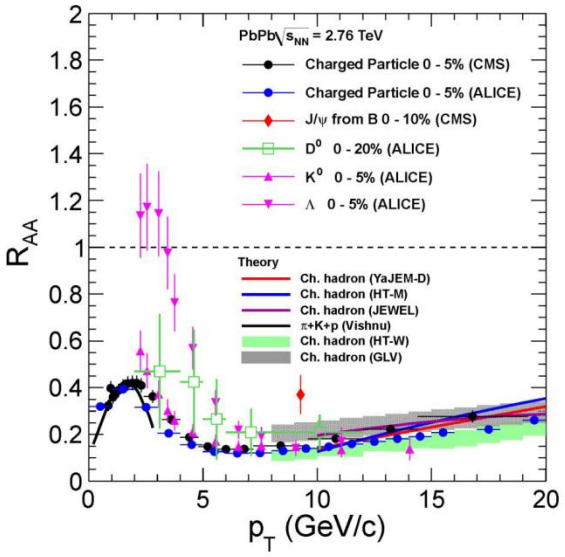
Lynnik et al., Nucl. Phys. A 786 (2007) 183

Charm production at threshold



charm in A+A at / near threshold: terra incognita
high discovery potential, e.g. inmedium modifications of D mesons





T or ρ ?

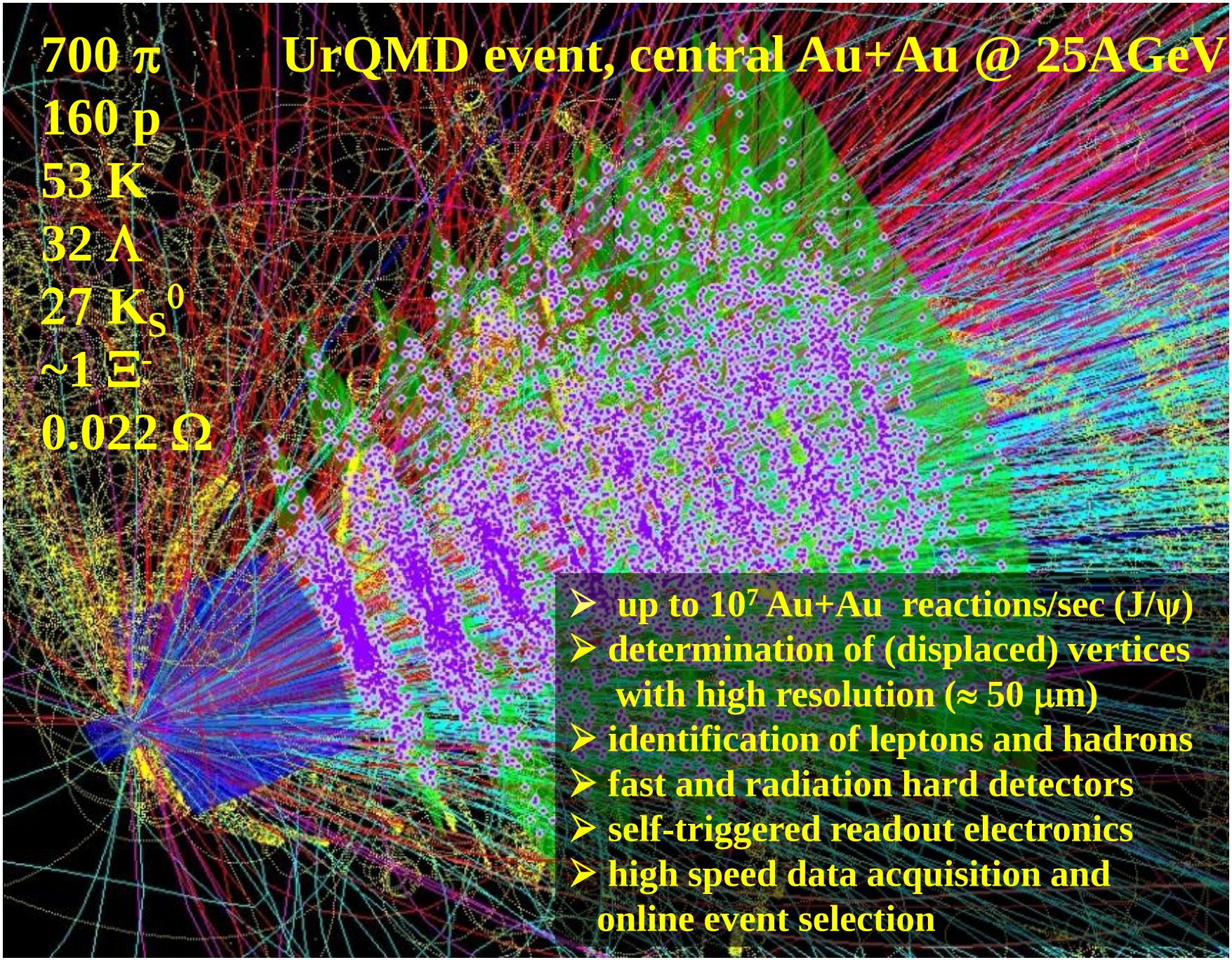
- **J/ψ and open charm suppression measured**
- **charmonium in hot and very dense matter?**
- **open charm in hot and very dense matter?**

$p + p \rightarrow J/\psi + p + p$ 11.2 GeV

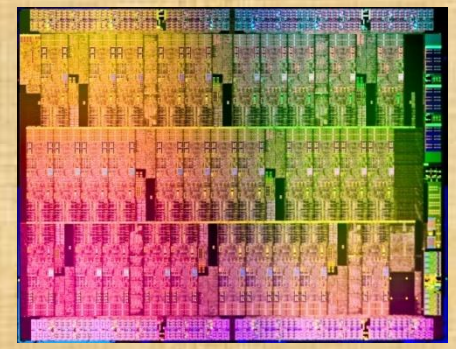
$p + n \rightarrow \Lambda_c + D^- + p$ 12.0 GeV

$p + p \rightarrow D^+ + D^- + p + p$ 14.9 GeV

Cold nuclear effects at low energy


700 π
160 p
53 K
32 Λ
27 K_S^0
~1 Ξ-
0.022 Ω
UrQMD event, central Au+Au @ 25AGeV
➢ up to 10^7 Au+Au reactions/sec (J/ψ)
➢ determination of (displaced) vertices with high resolution (≈ 50 μm)
➢ identification of leptons and hadrons
➢ fast and radiation hard detectors
➢ self-triggered readout electronics
➢ high speed data acquisition and online event selection

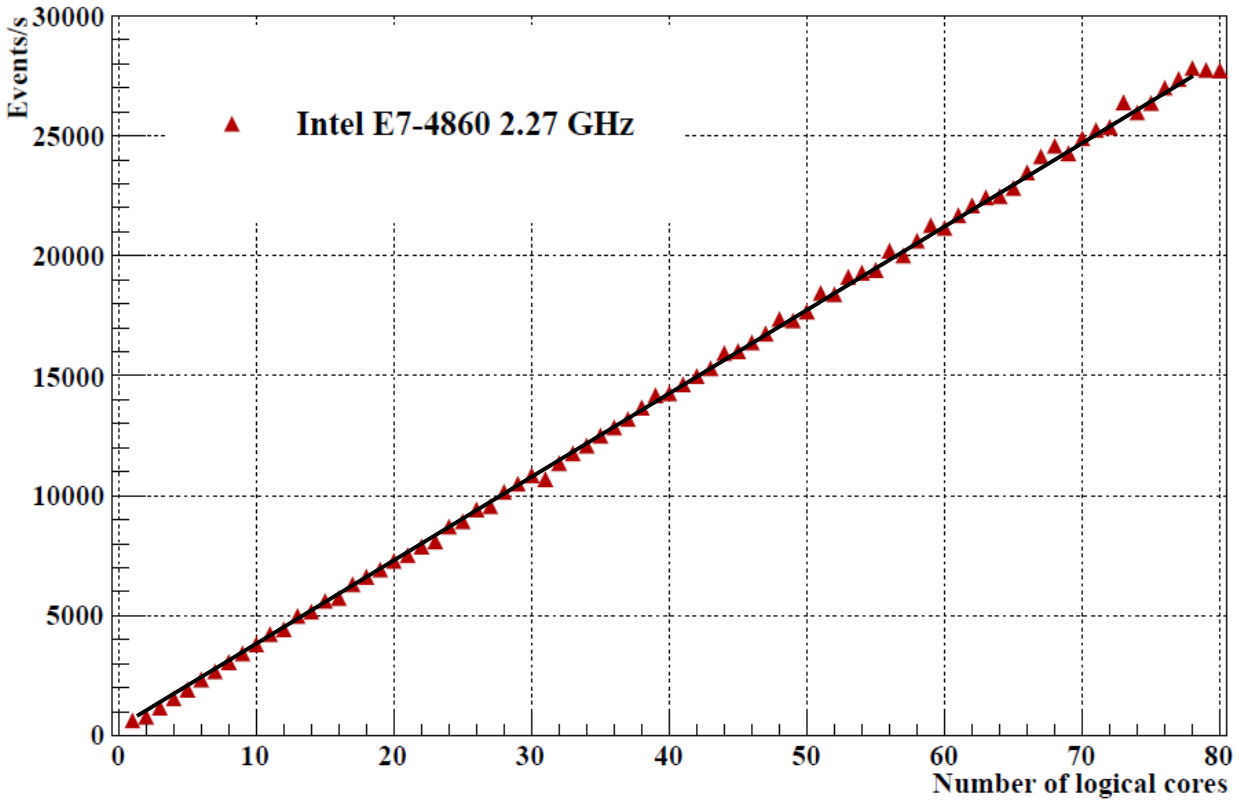
Welcome to the multi-core era!



Intel E7-4860

Simulation & reconstruction
80k UrQMD
02.2012

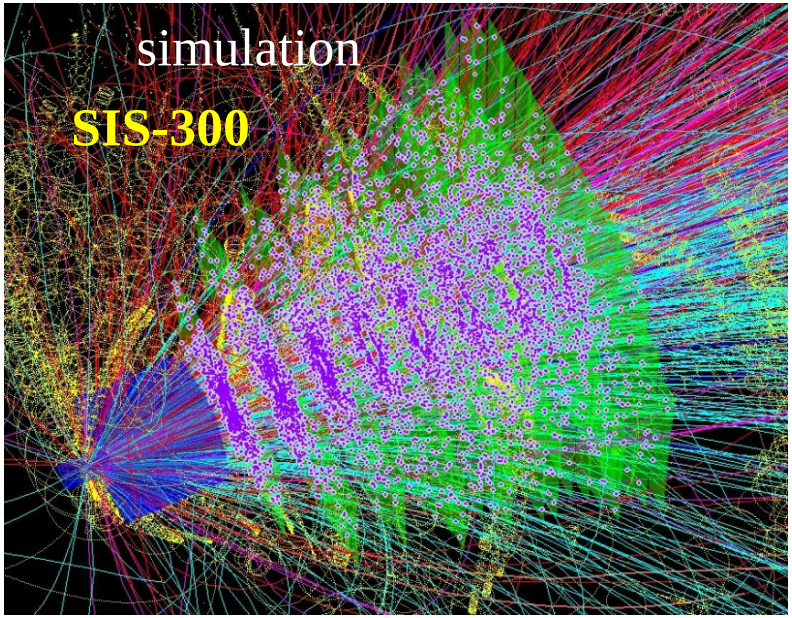
80 cores GSI



Developer's World 2012

central Au+Au @ 25AGeV

600 reconstructed tracks
Ref. prim. eff = 96%
All set eff = 86%
dp/p = 1.2%



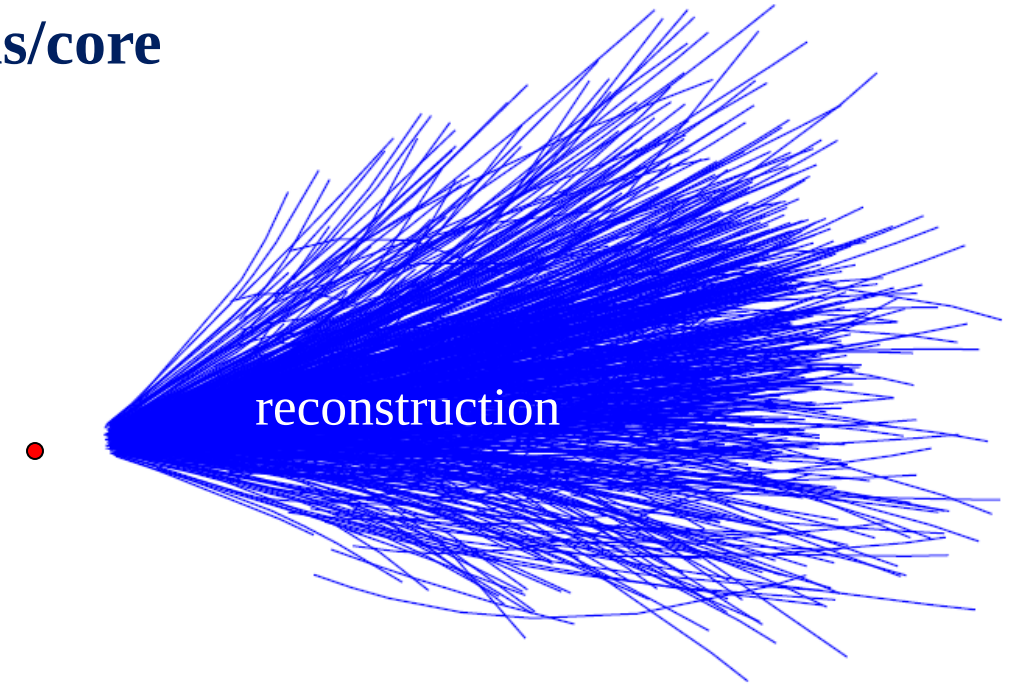
700 π
160 p
53 K
32 Λ
27 K_S^0
~1 Ξ^-
0.022 Ω^-

10MHz

SIMDized tracking + KFParticle

Track finder, central: 62+11.7 ms/core
mbias : 8+1.5 ms/core
up to 80 cores/CPU

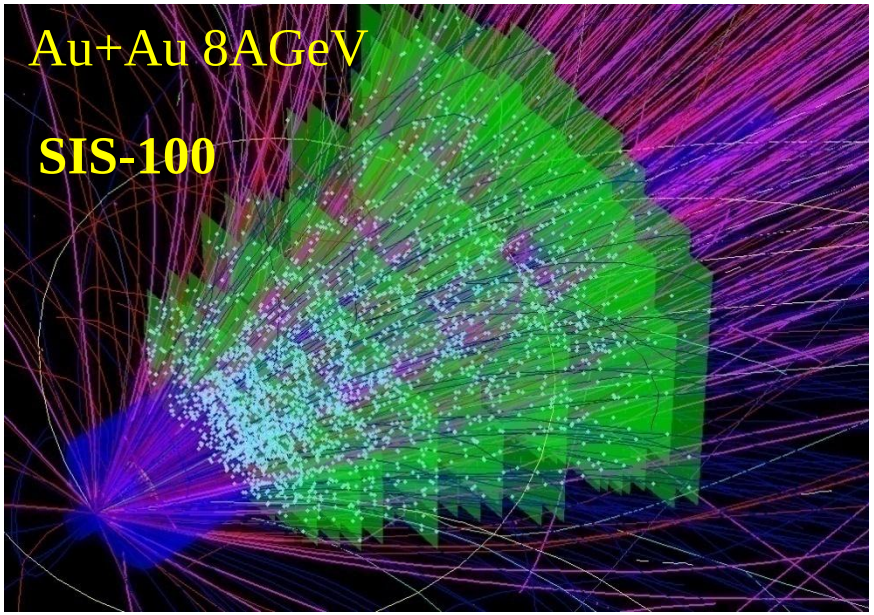
FLES: track finder, track fitter,
PV finder, **V^0** (K^0_s and Λ) finder,
Ξ^-, Ω^-, Σ^{*+}, Σ^{*-}, K*,..
J/ψ, D^0, D^+, ρ, ω, ϕ ...
finder



Functionality in ALICE and CBM

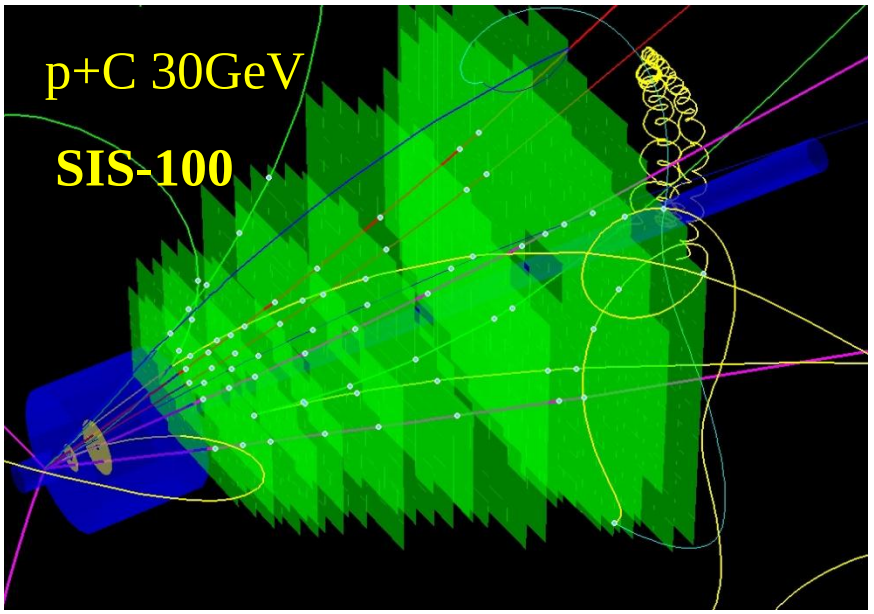
Functions	ALICE	CBM
Construct, SetMassConstraint, SetProductionVertex, SetVtxGuess	+	+
GetMass, GetMomentum, GetDecayLength, GetLifeTime	+	+
GetDecayLengthXY, GetPhi, GetR	+	
Extrapolate, TransportToProductionVertex(), TransportToDecayVertex()	+	+
TransportToPoint, TransportToVertex, TransportToParticle, TransportToDS,	+	
GetDStoPoint	+	+
GetDStoParticle, GetDStoParticleXY, GetDistanceFromVertex, GetDistanceFromVertexXY, GetDistanceFromParticle, GetDistanceFromParticleXY, GetDeviationFromVertex, GetDeviationFromVertexXY, GetDeviationFromParticle, GetDeviationFromParticleXY	+	
GetAngle, GetAngleXY, GetAngleRZ	+	
SubtractFromVertex, ConstructGamma	+	
SetNoDecayLength, +=, -=	+	
Particles finder		+

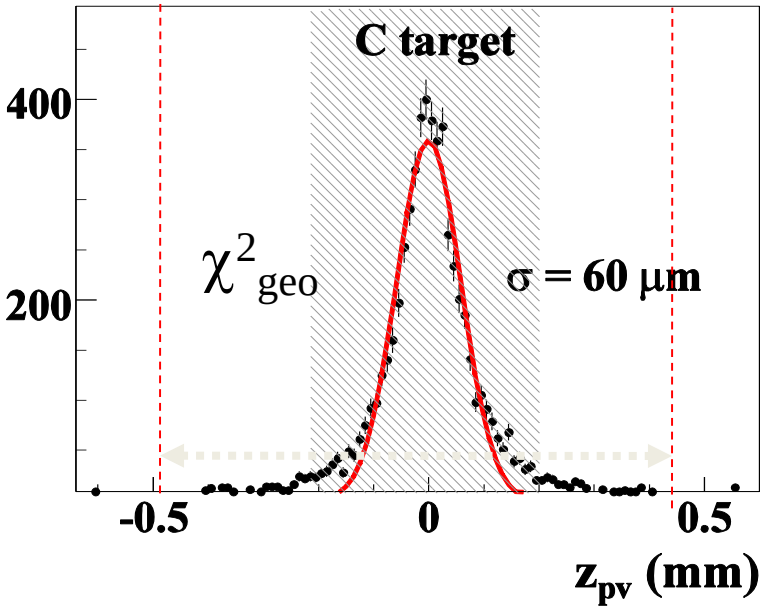
Functionality becomes more and more advanced



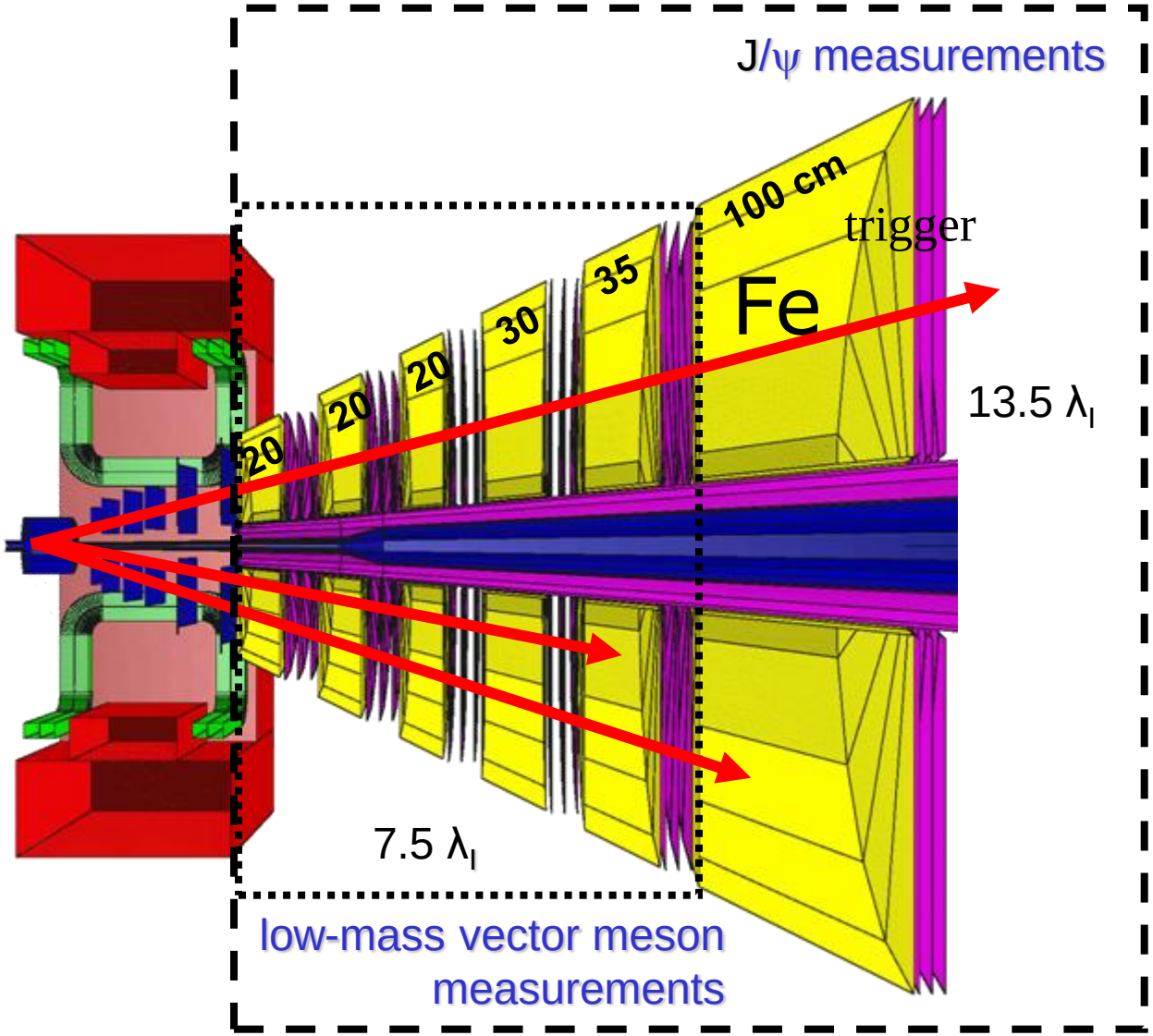
Au+Au 8AGeV	
pi+	140.97
pi-	165.62
p	168.97
K+	17.15
K-	2.34
K^0	17.43
aK^0	2.22
Λ	14.23
Σ^0	4.64
Ξ^-	0.268
Ω^-	0.005

p+C 30GeV	
pi+	2.39
pi-	2.12
p	6.65
K+	0.17
K-	0.08
K^0	0.17
aK^0	0.08
Λ	0.1
Σ^0	0.033
Ξ^-	0.0013
Ω^-	0.0000

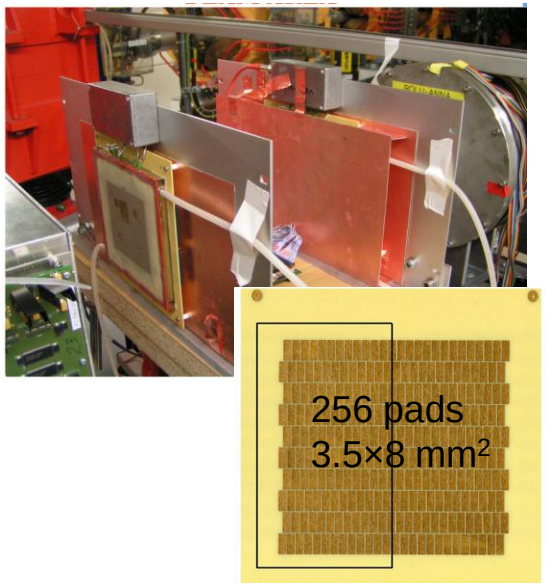




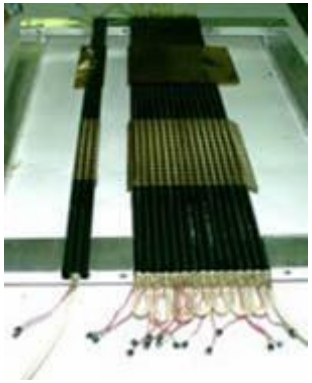
Charmonia (di-muon channel)



GEM detectors



Straw tubes

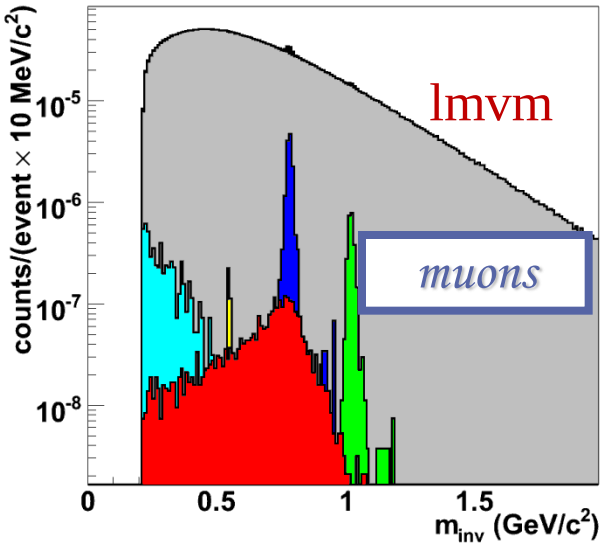


Charmonia (di-muon channel)

- Signal and background yields from physics event generators (HSD, UrQMD)
- Full event reconstruction based on realistic detector layout and response

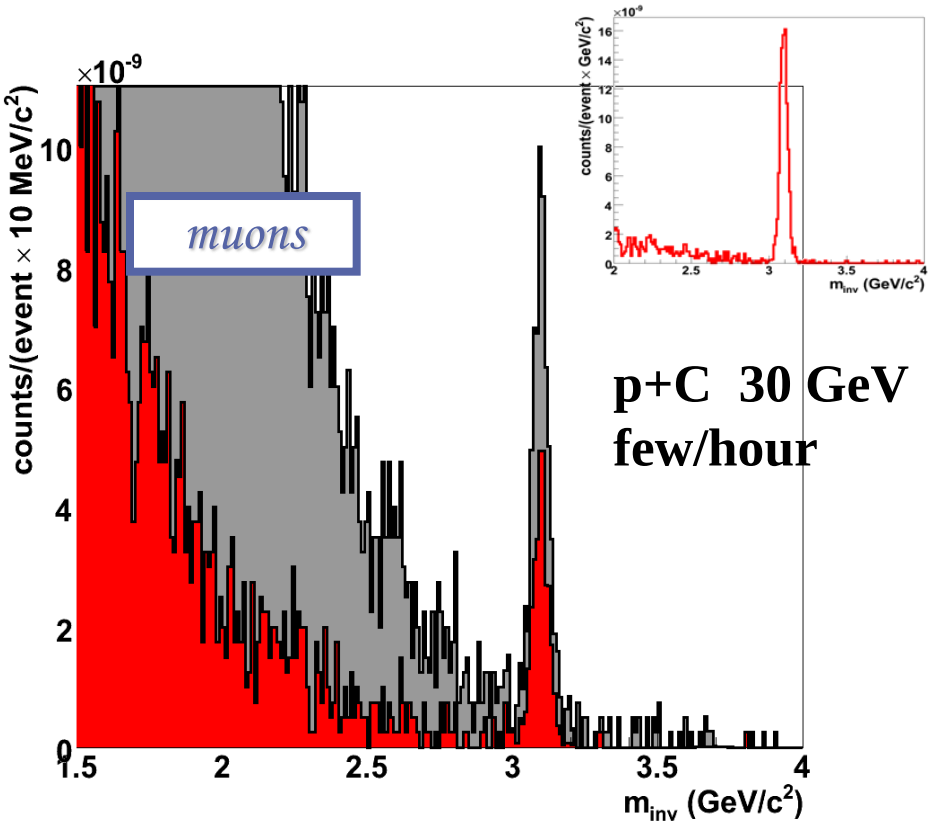
$J/\psi \rightarrow \mu^+\mu^-$

	S/B ratio	ε [%]	σ_M [MeV]
ω	0.08	3.7	10
ϕ	0.03	6	12
ρ	0.001	2.7	



130 ρ/h
600 ω /h
90 φ/h

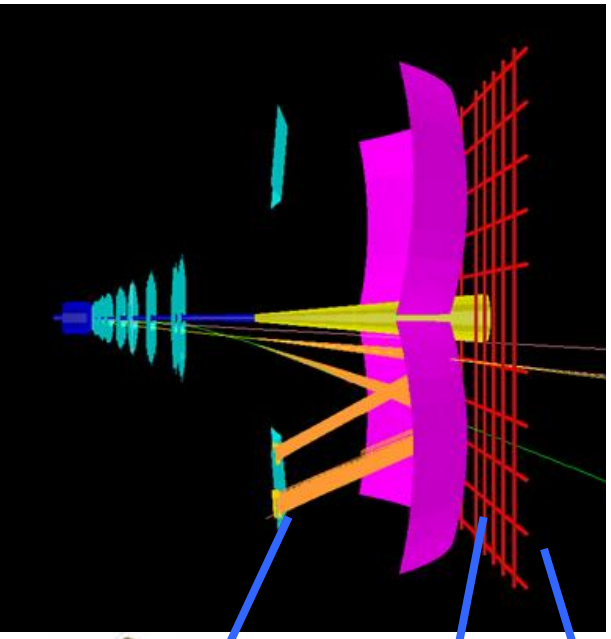
Au+Au 35 AGeV

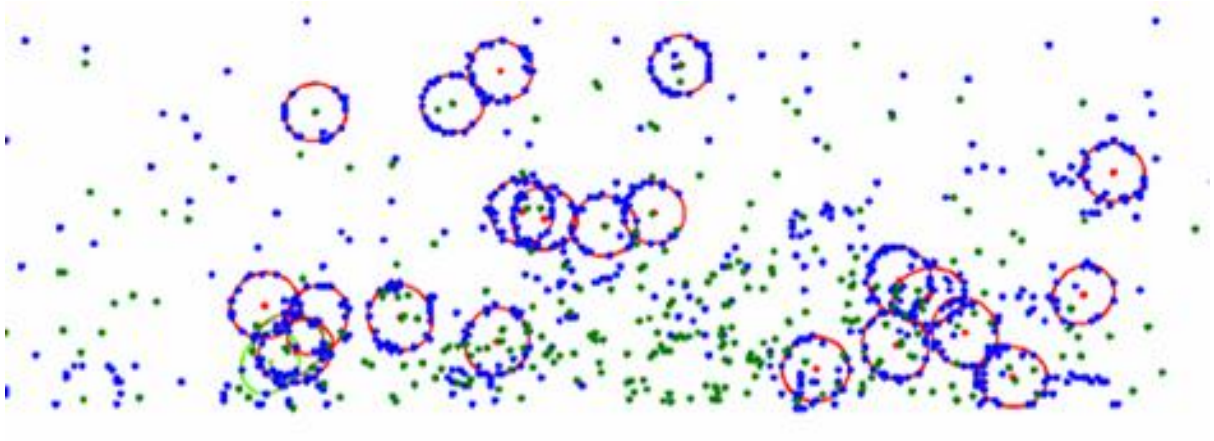


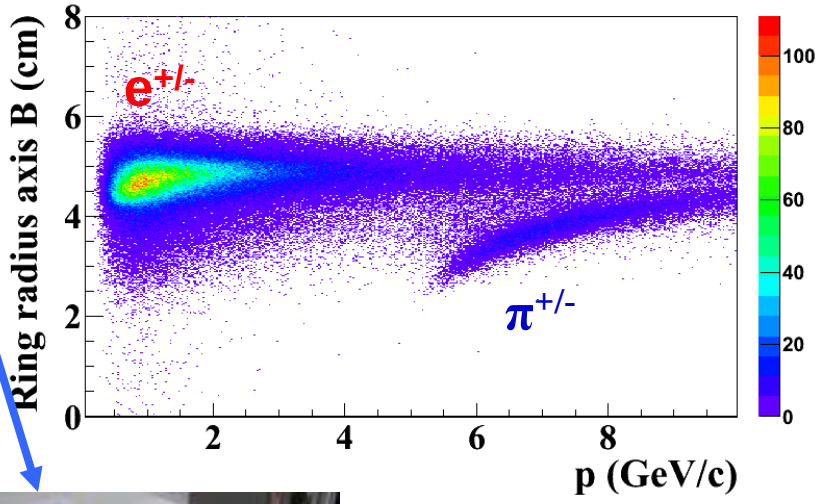
p+C 30 GeV
few/hour

~600 J/ψ per hour

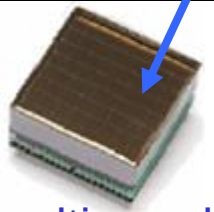
Charmonia (di-electron channel)







Rings:
up to 100 per event
~ 6cm diameter
~ 20 photo electrons
finding eff. **95.3%**



multi-anode PMT

glass mirror with Al+MgF_2

high-rate TRD

RICH + TRD:

e identification efficiency	**85 %**
π-suppression	**10^4**

Charmonia (di-electron channel)

- Signal and background yields from physics event generators (HSD, UrQMD)
- Full event reconstruction based on realistic detector layout and response

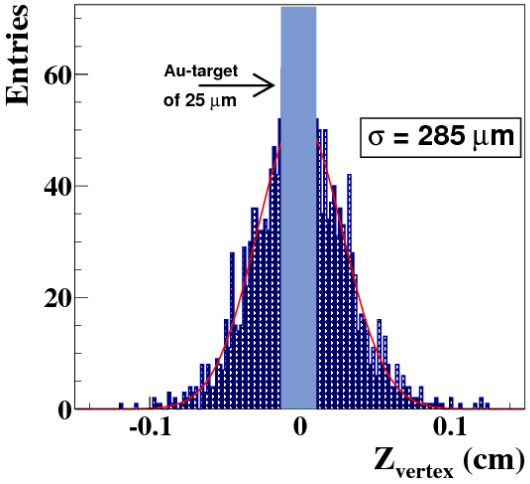
Electron id:

RICH and TRD

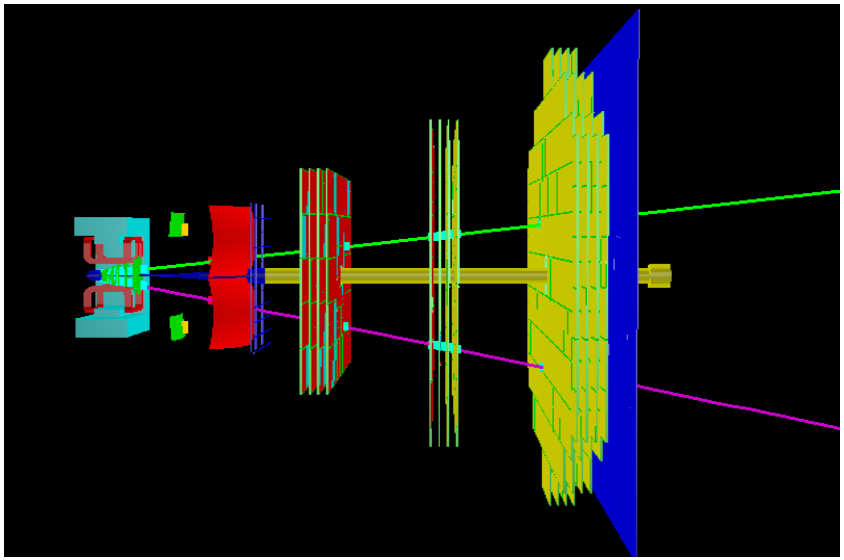
π suppression: factor **10^4**

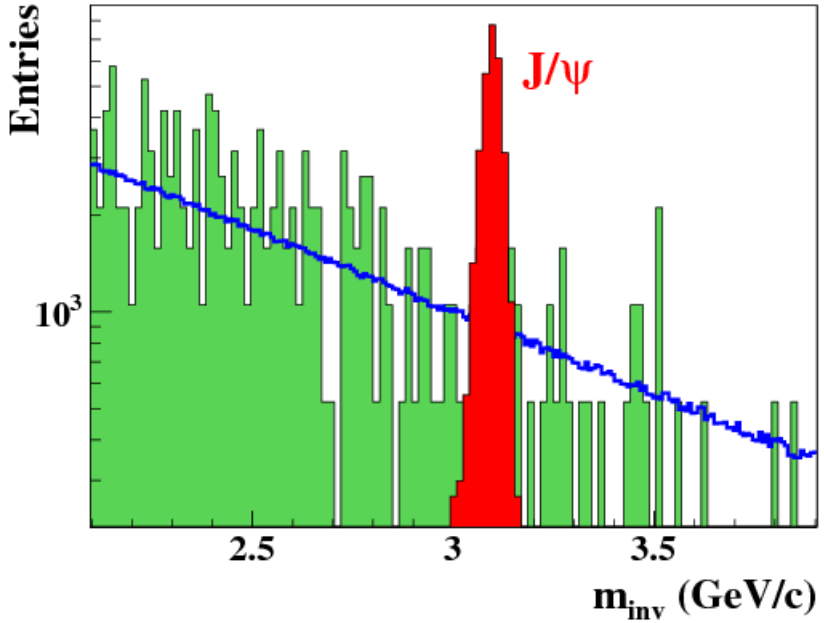
dominant background:
e from π^0 Dalitz

KFParticle - vertexing:
Background suppression
γ-conversion, π^0 Dalitz



4× 10^{10} events



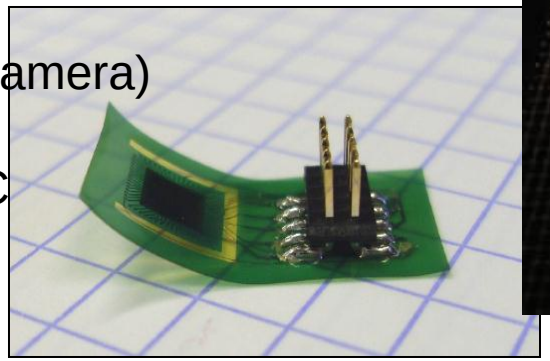


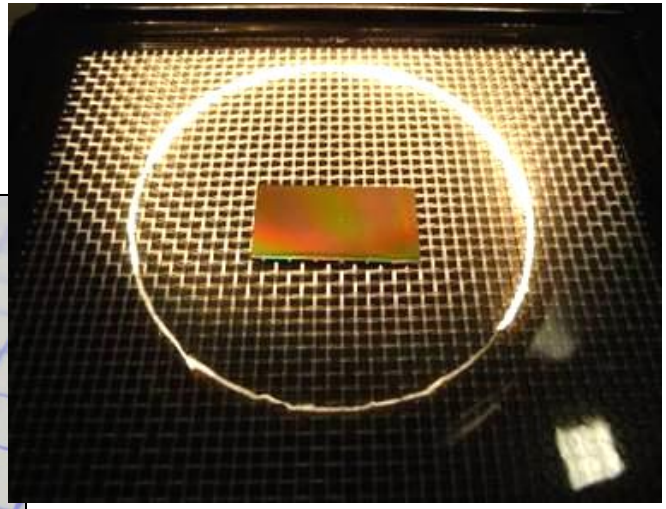
Mission Open Charm: Primary vertex reconstruction

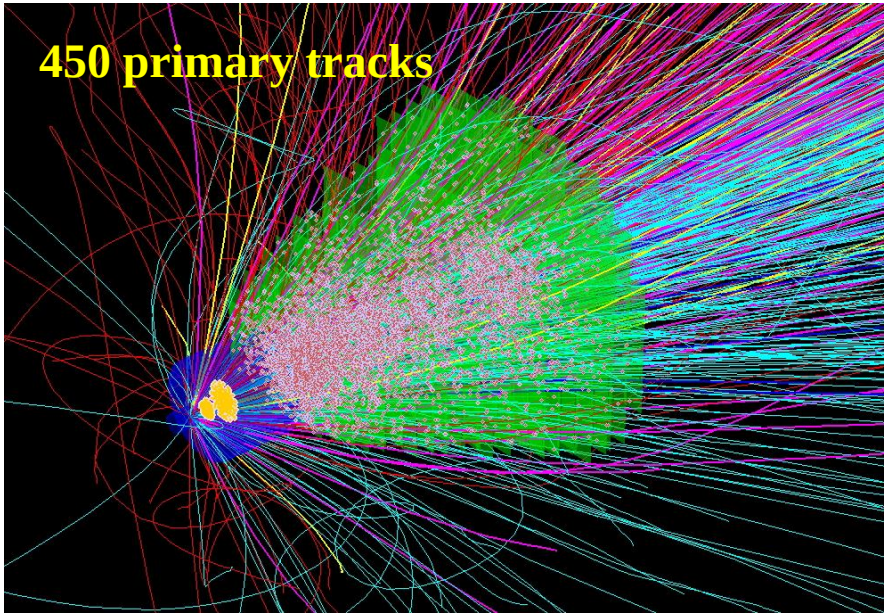
Au+Au @ 25AGeV

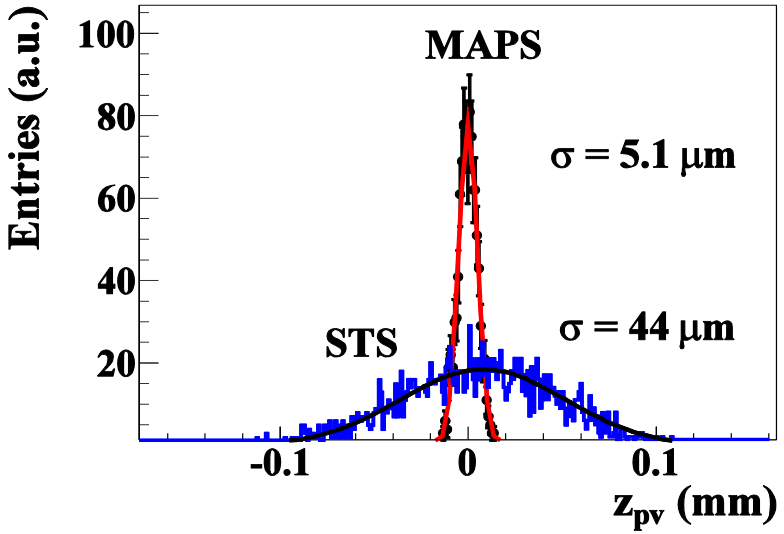
Monolithic Active Pixel Sensors
(MAPS, also CMOS-Sensors)

- Invented by industry (digital camera)
- Modified for charged particle detection since 1999 by IPHC Strasbourg
- Also foreseen for STAR…





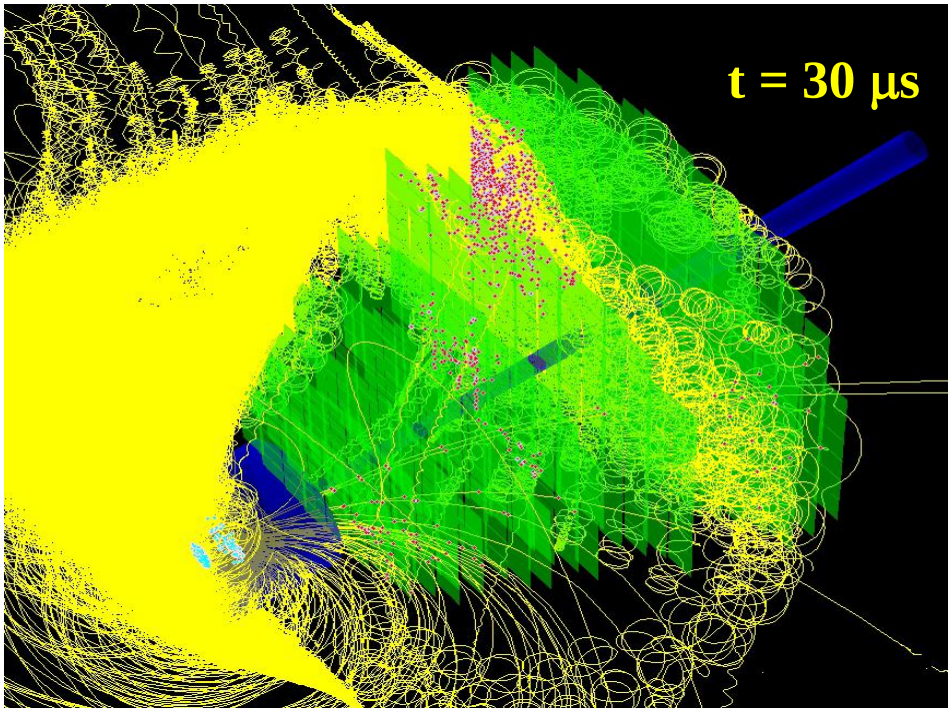


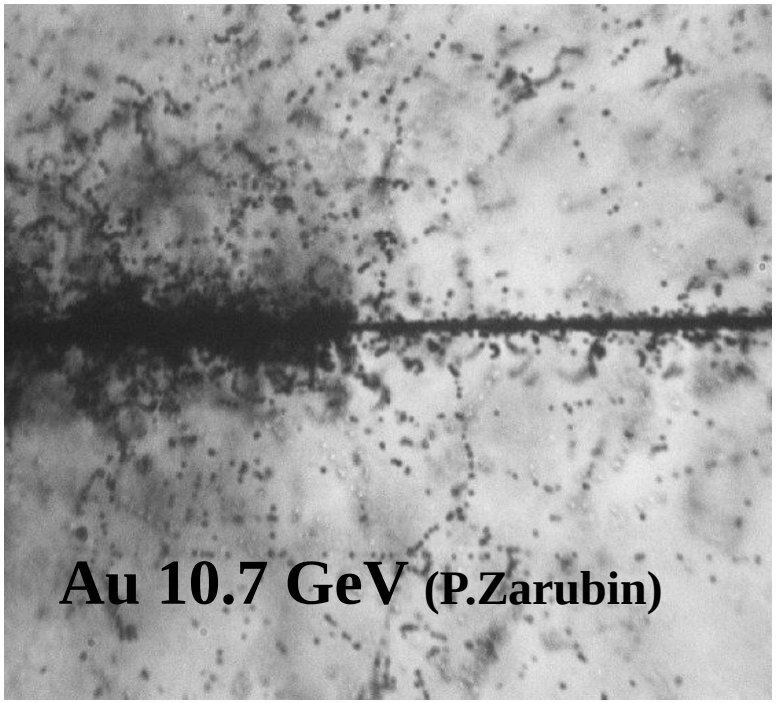


450 tracks central
100 tracks mbias

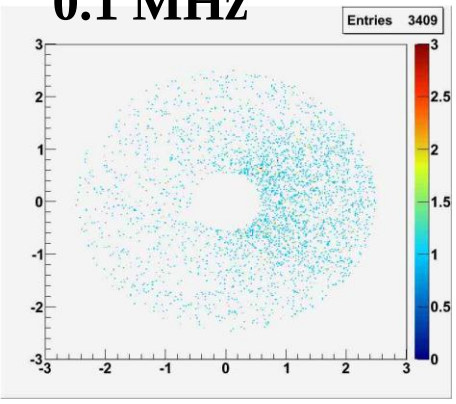
Au+Au @ 25AGeV δ-electrons = reconstruction time !

IR: 0.1MHz = 300 Au ions

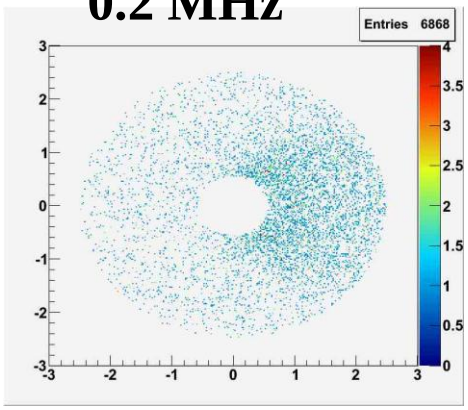




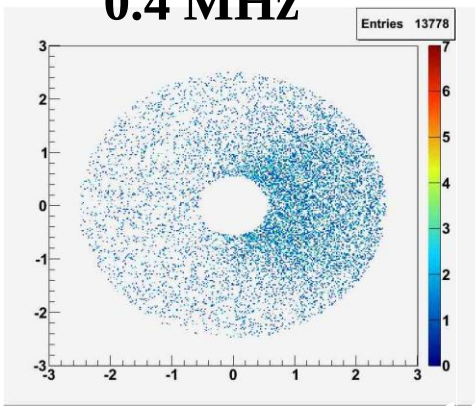
0.1 MHz



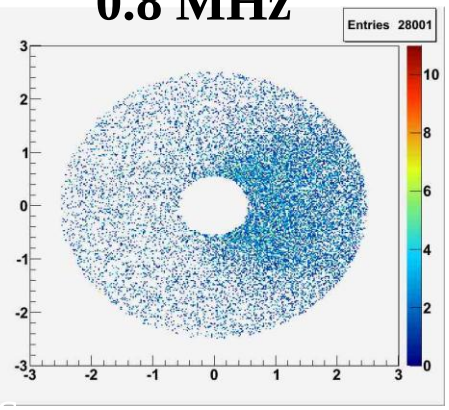
0.2 MHz



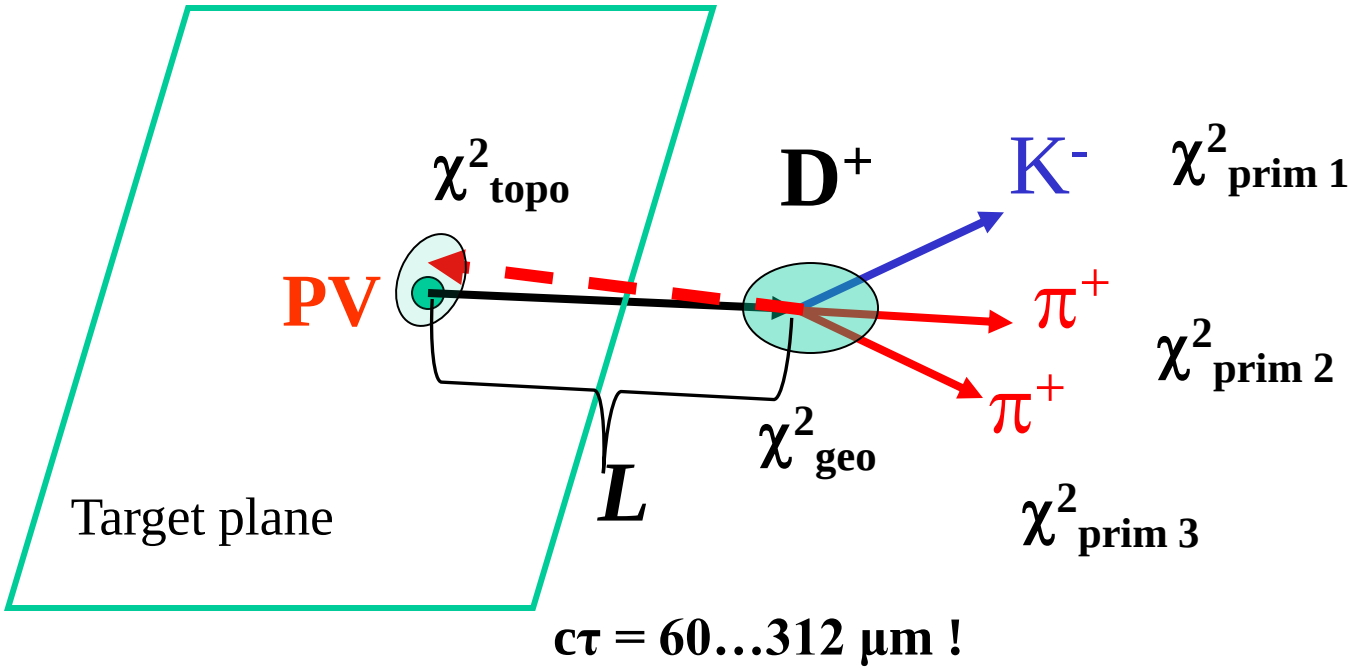
0.4 MHz



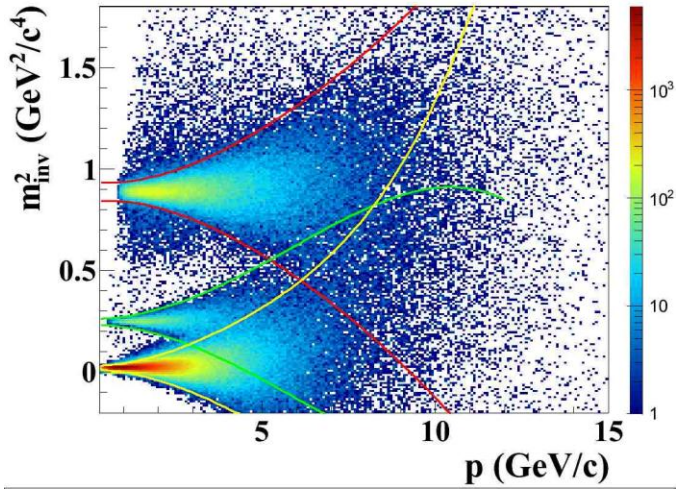
0.8 MHz



Open charm decay topology



Strategy: background suppression keeping maximum of efficiency



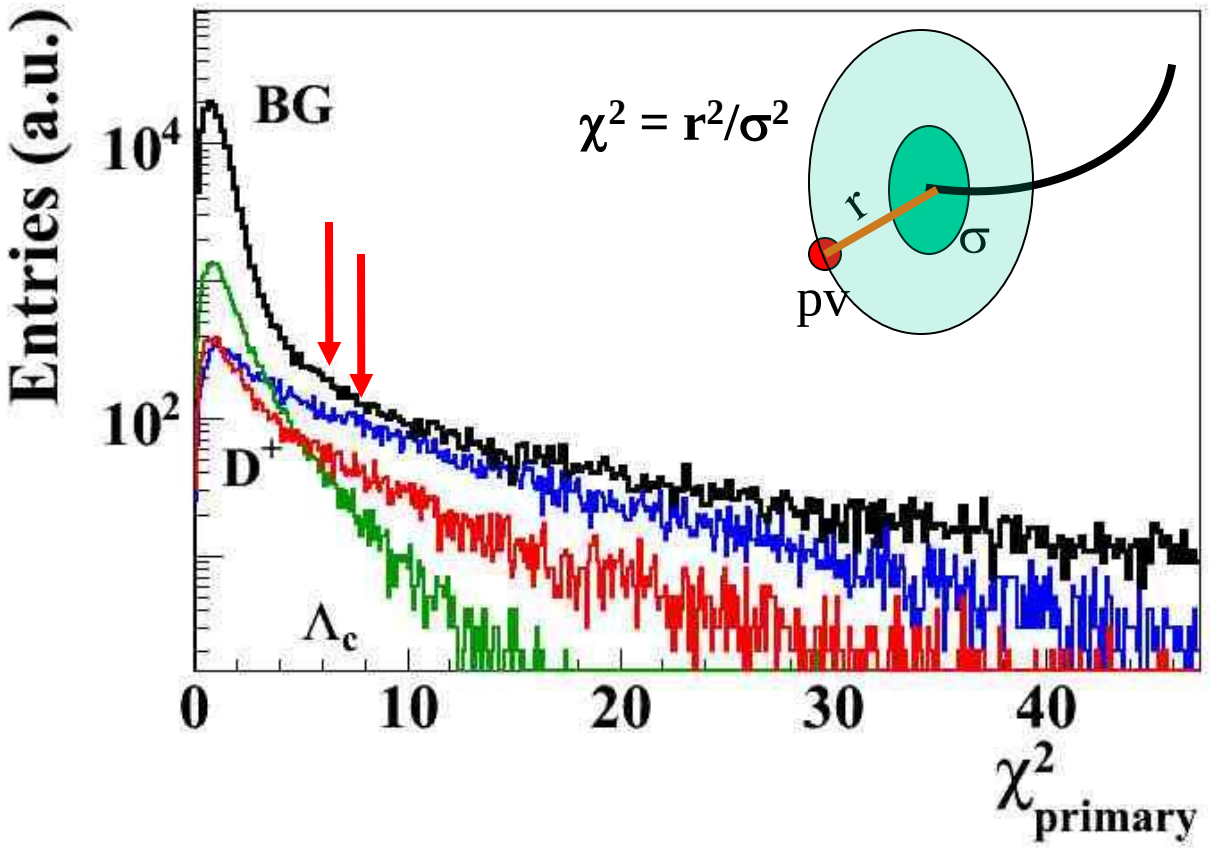
single track parameters based cuts:

- χ^2_{prim} impact parameter value 6.0-7.5
- **IP** impact parameter cut (upper value) 0.5 mm
- protons ID by TOF
- *track transverse momentum* $p_t > 0.3$ *GeV/c* (D^0 *only*)

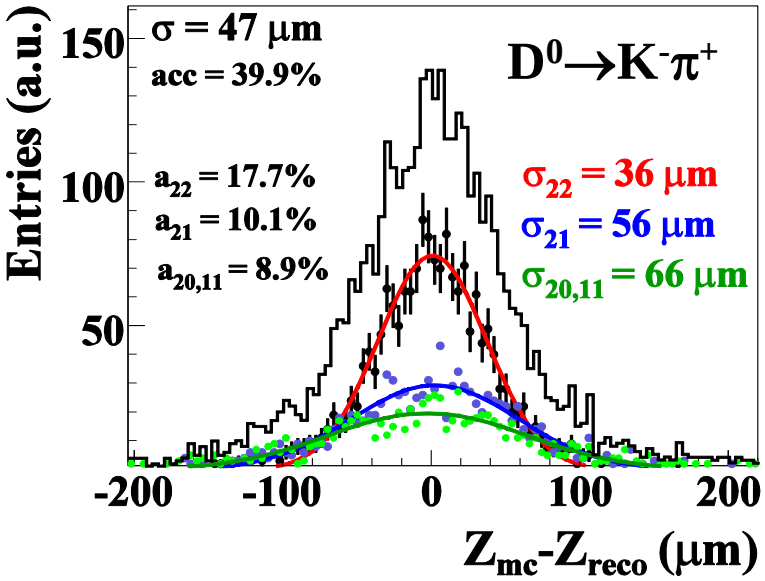
multiple track (**KFParticle**) parameters based cuts:

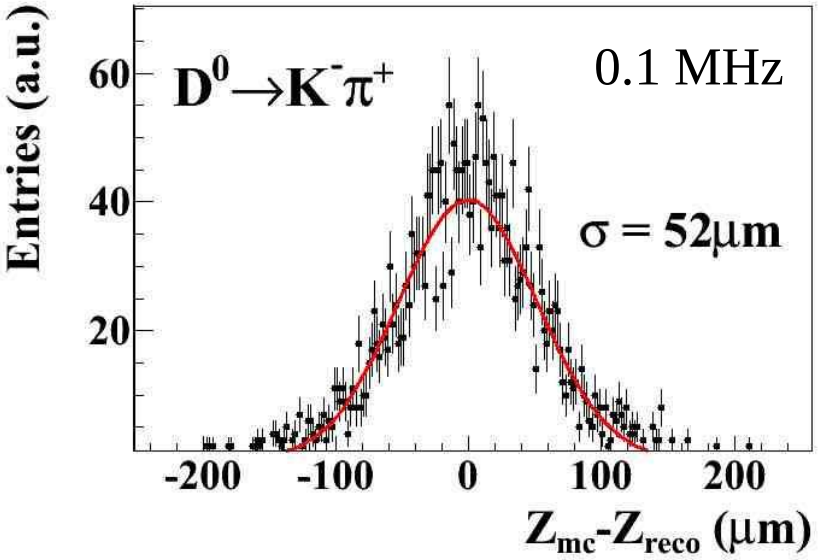
- χ^2_{GEO} geometrical constrained fit 3.0
- χ^2_{TOPO} topological constrained fit 2.0-3.0
- charm **KFParticle** to primary vertex DCA < 20(30) μm
- Z_{vertex} **< 2(3.5) mm** Λ_c

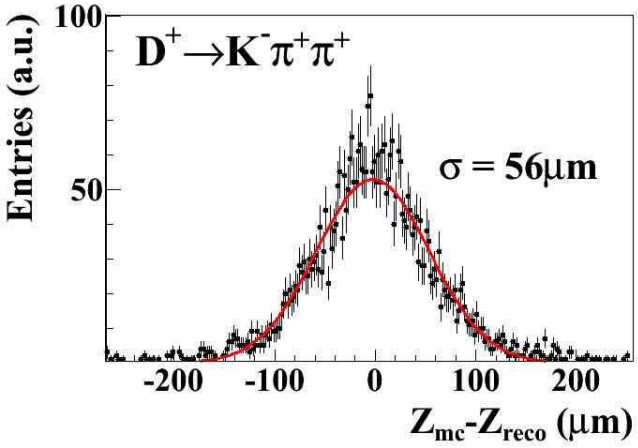
χ^2_{prim} impact parameter value 6.5-7.5

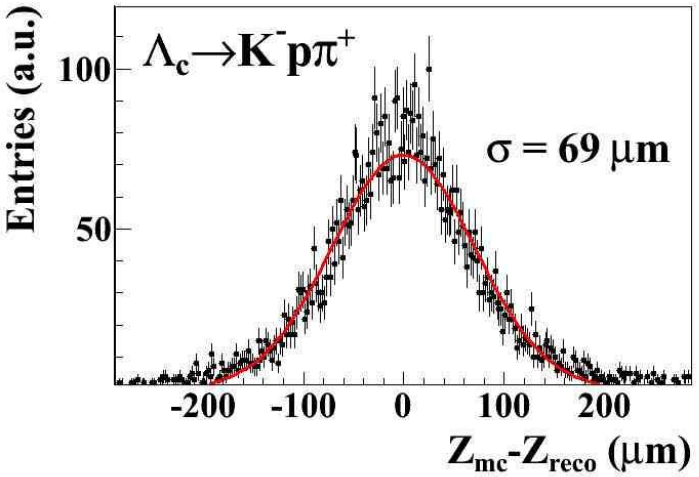


Open charm (Au+Au @ 25 AGeV)
z-vertex reconstruction

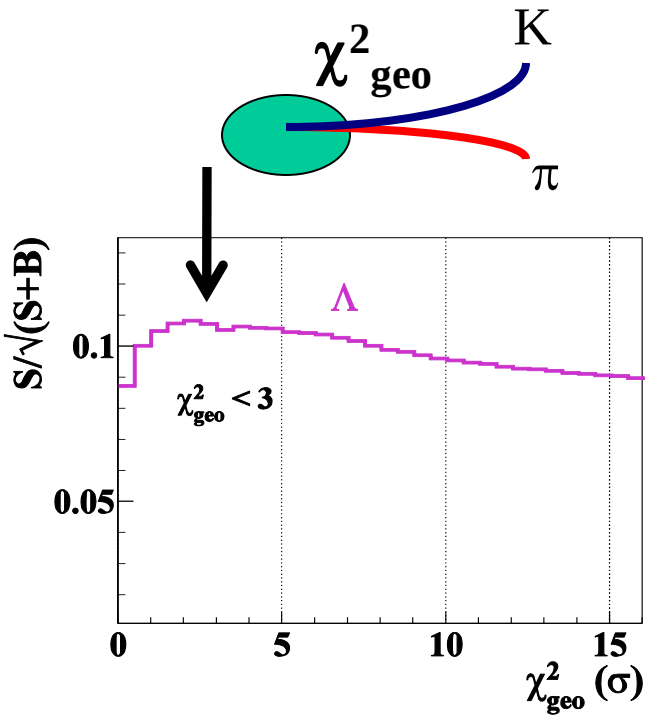


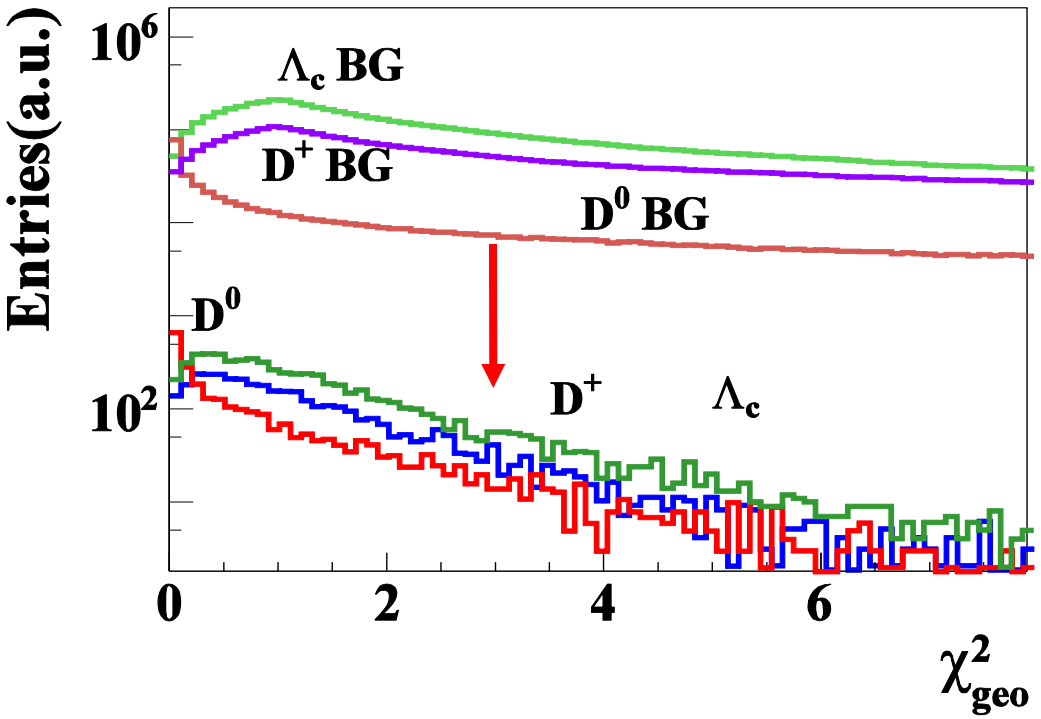




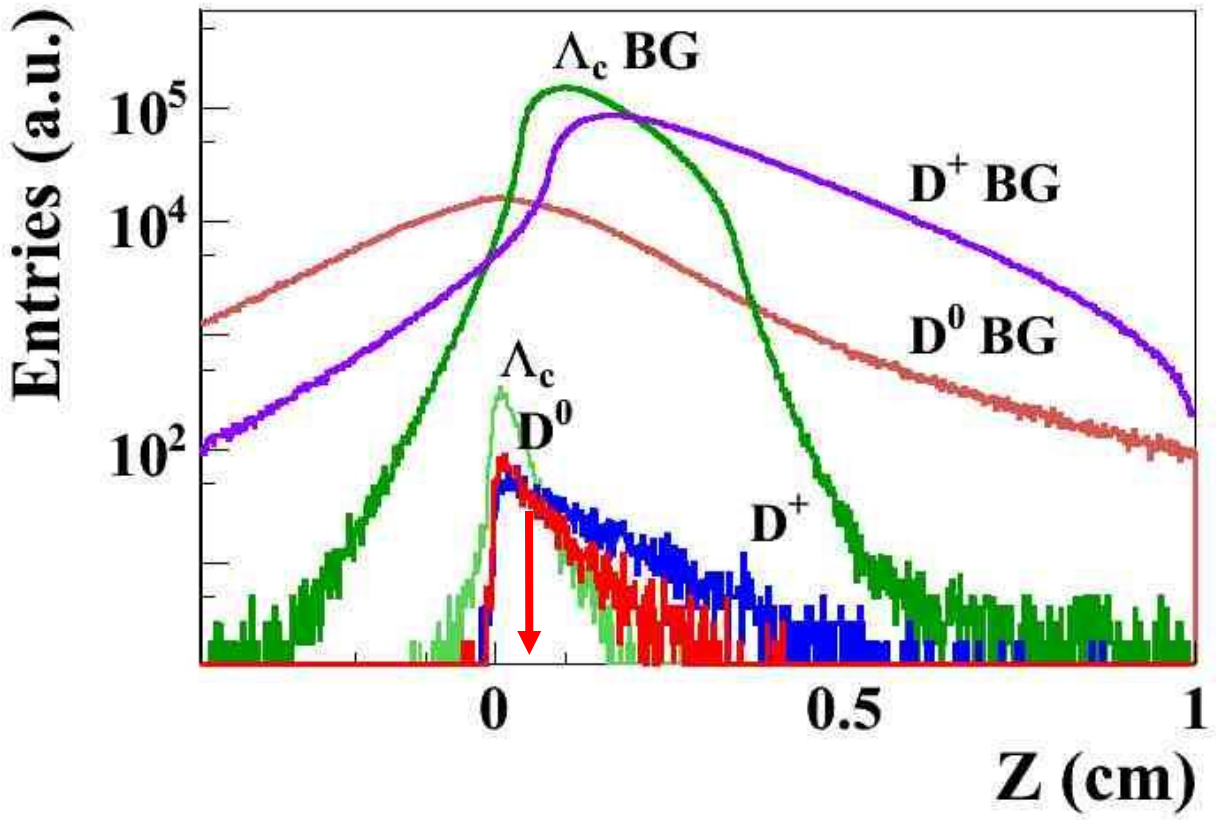


KFParticle χ^2_{geo} geometrical constrained fit < 3.0

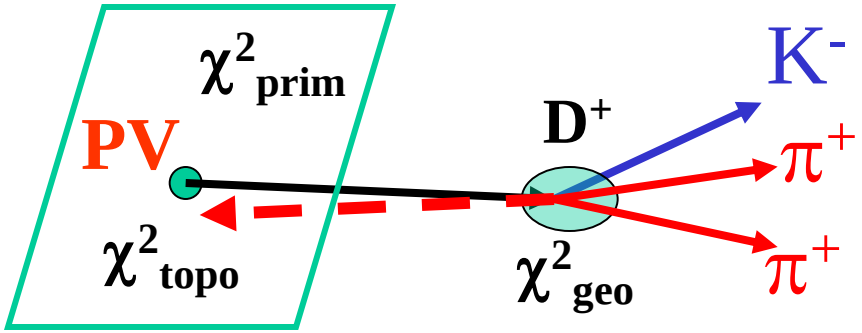


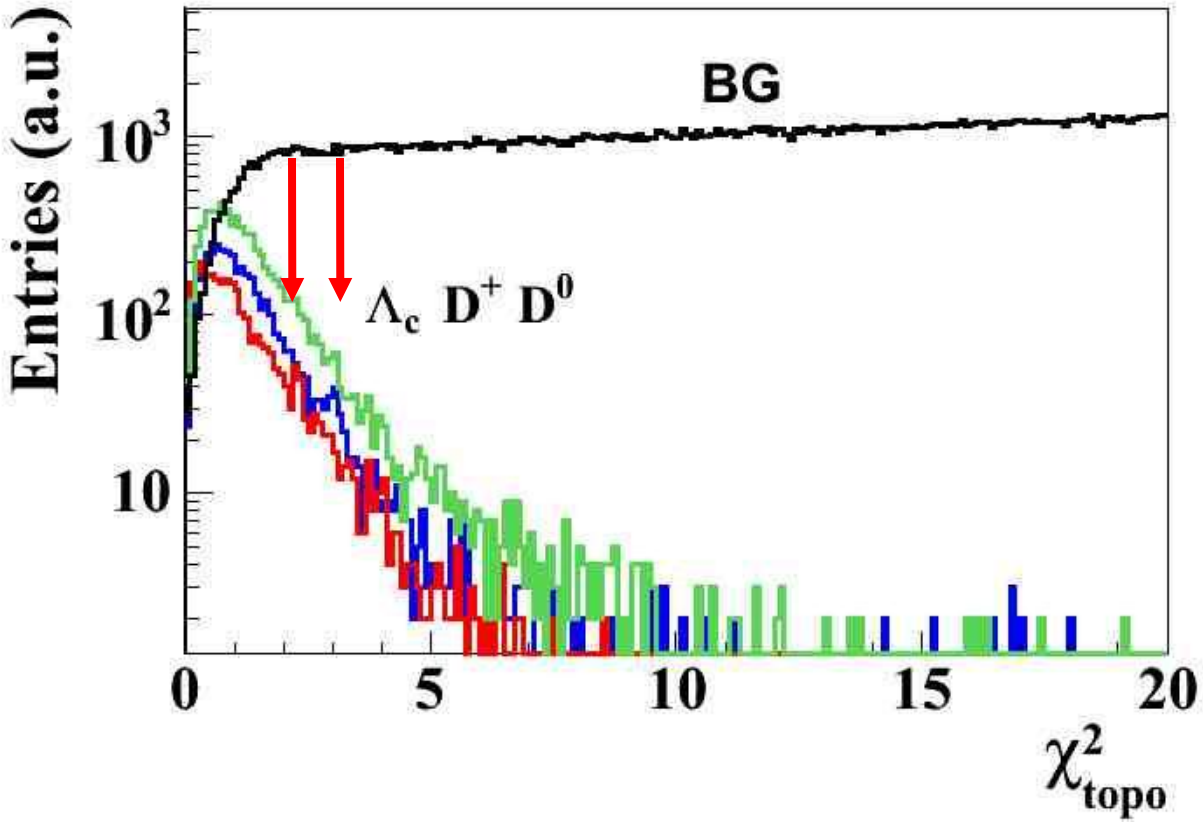


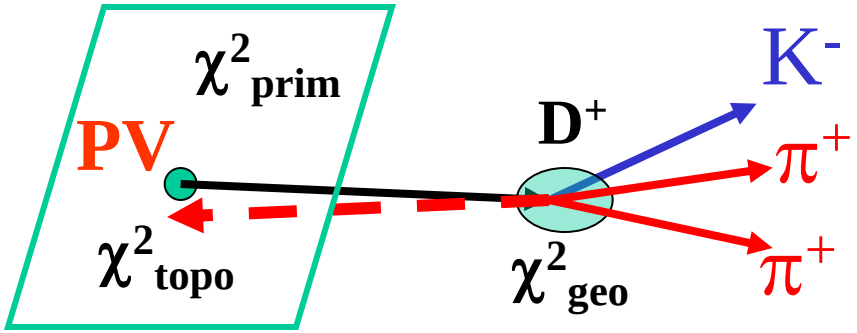
KFParticle $Z_{vertex\ geo} > 350\ \mu m$



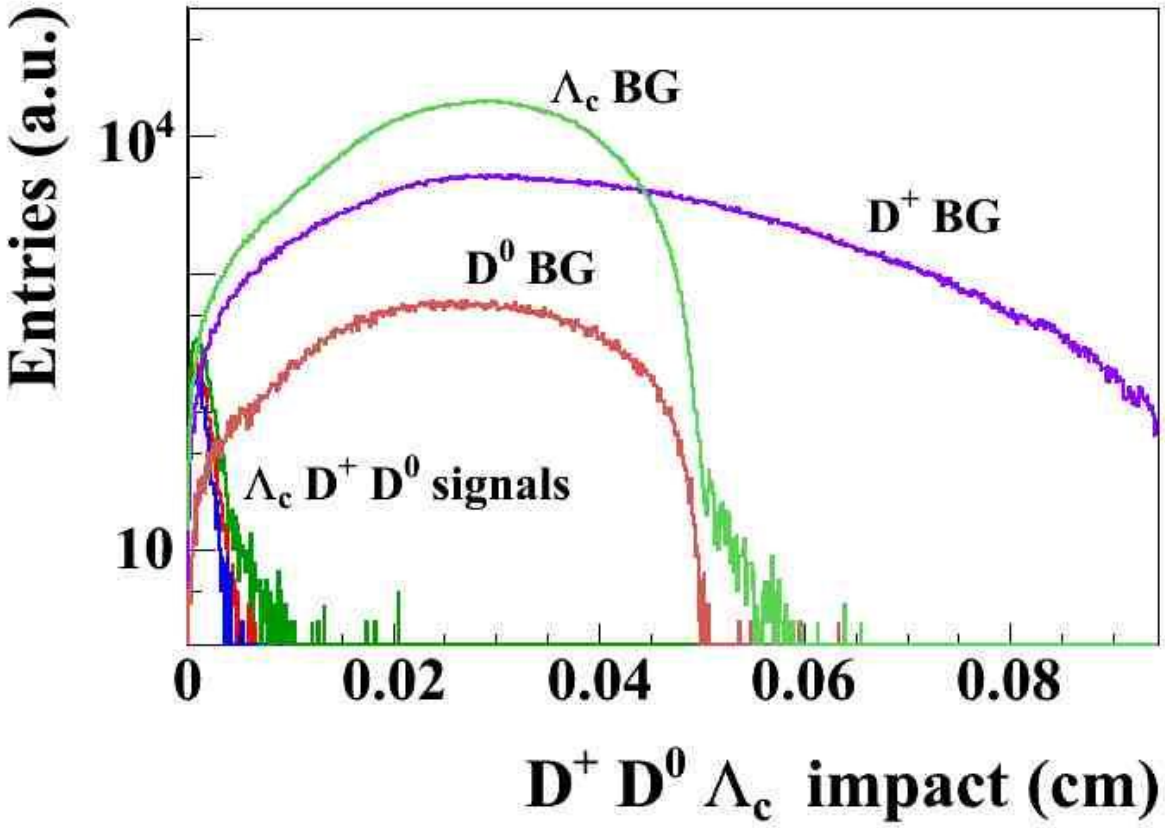
KFParticle χ^2_{topo} topological constrained fit 2.0-3.0



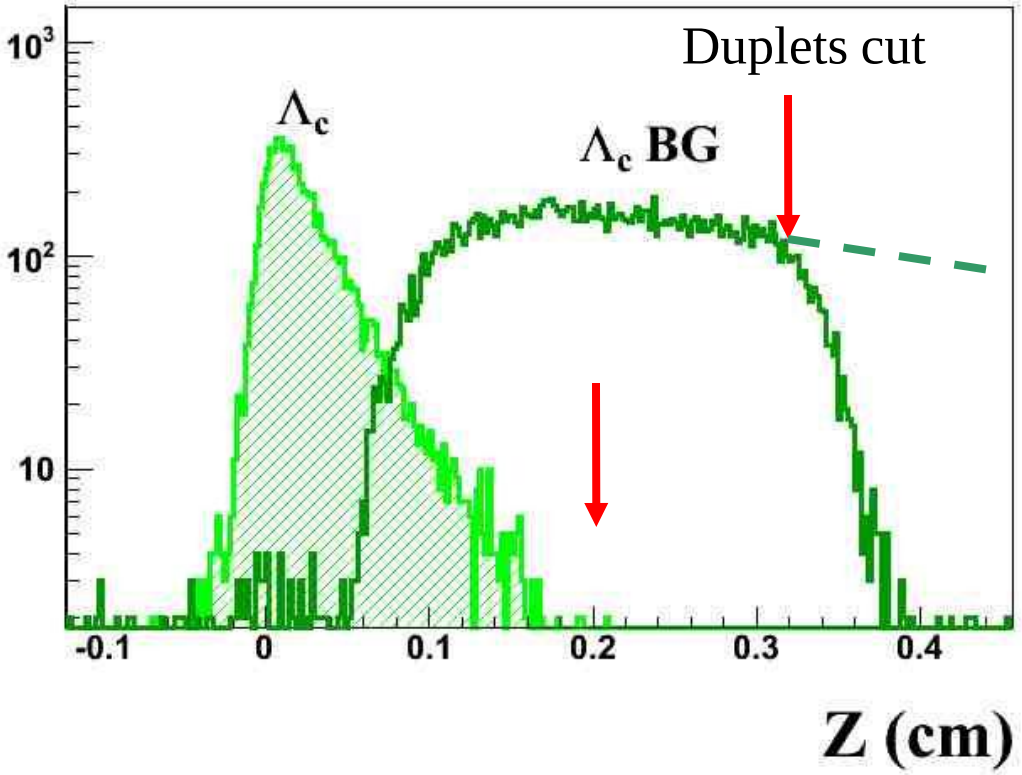




charm **KFParticle** impact parameter < 3σ (20 μm)

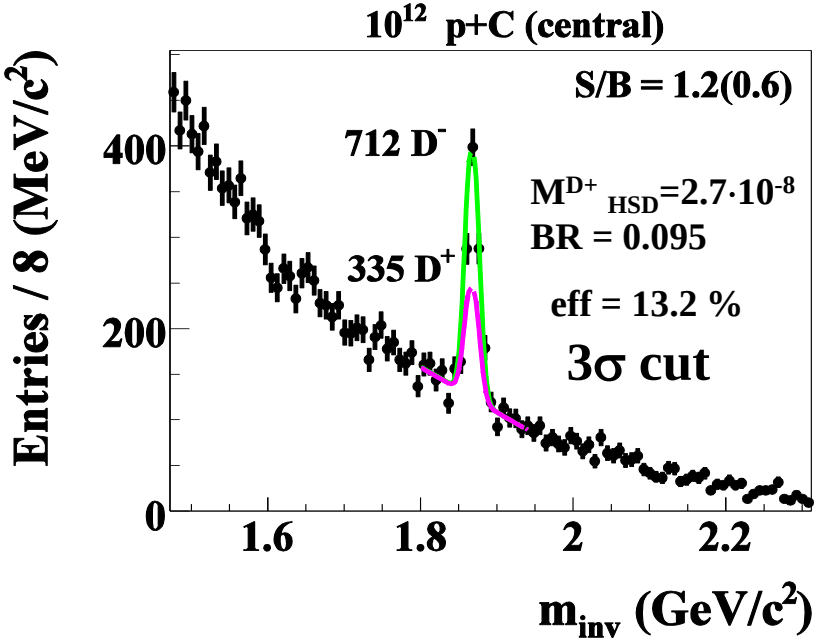


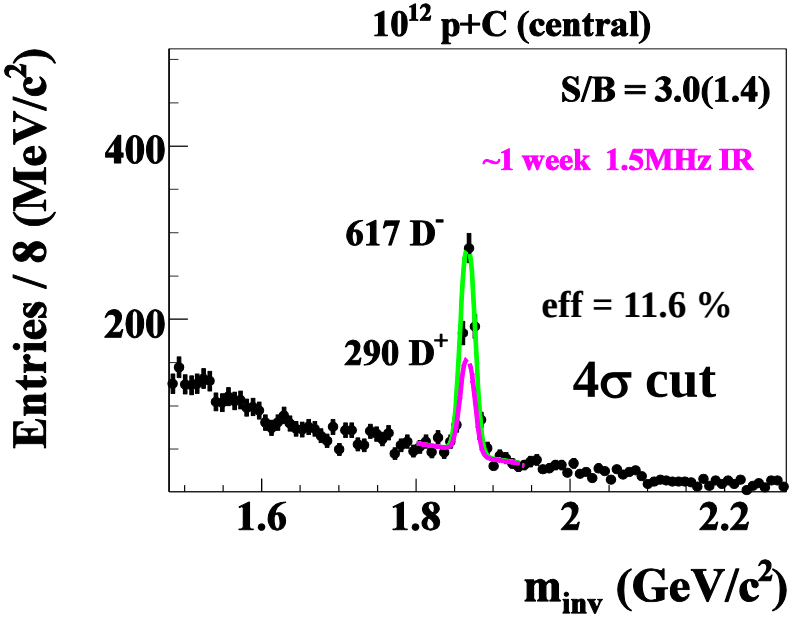
KFParticle Z_{vertex} < 2 mm



Open charm at SIS-100
Invariant mass spectra

p+C 30GeV $D^+ \rightarrow K^- \pi^+ \pi^+$



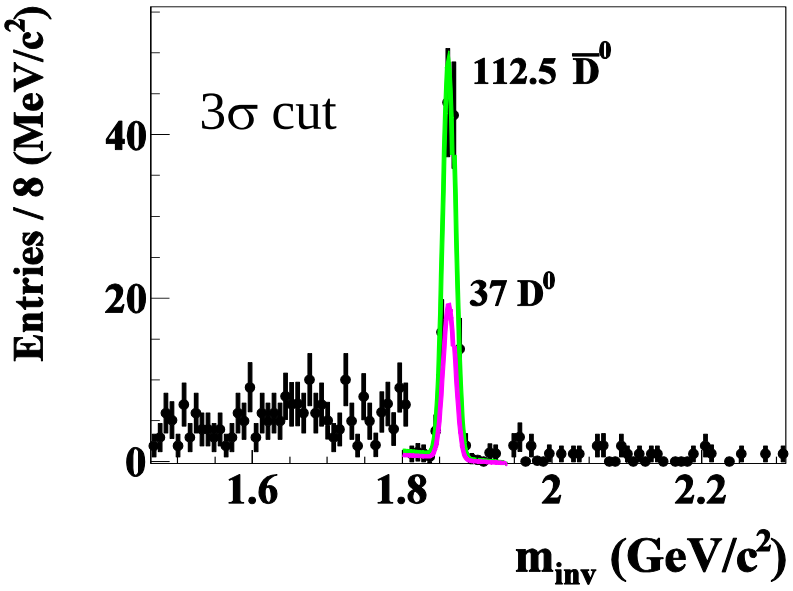


with PV BG suppressed 10-30 times!

Invariant mass spectra

p+C 30GeV

10^{12} central events



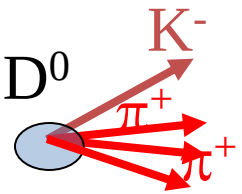
$D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$

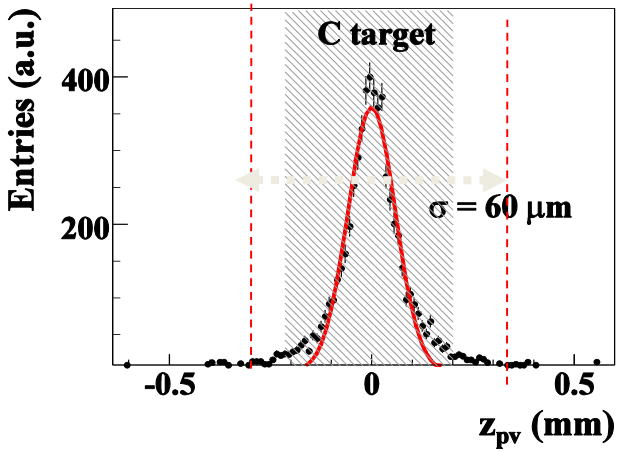
$M^{D0}_{HSD} = 2.9(8.8)\cdot 10^{-8}$

BR = 7.7%

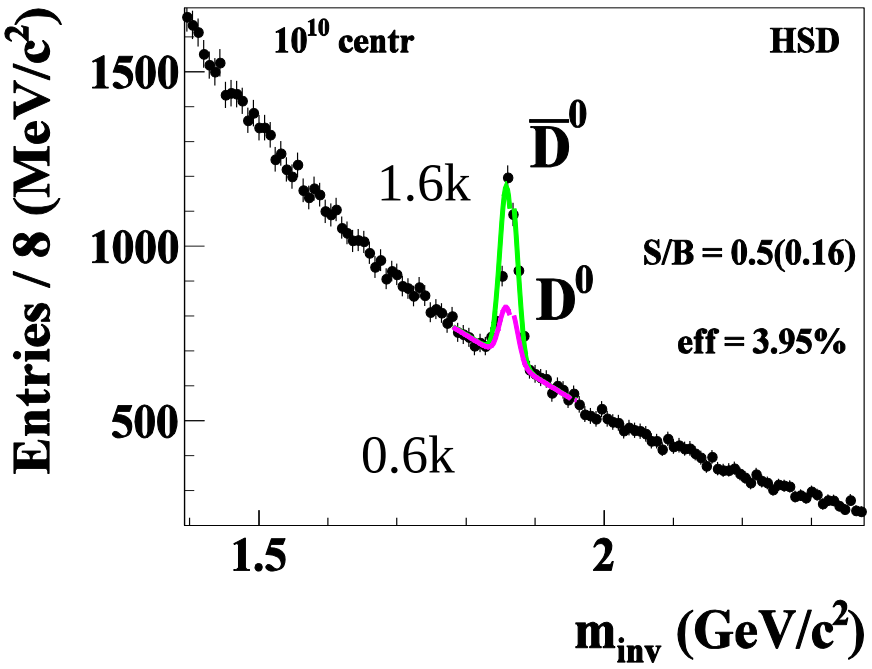
Eff = 1.7%

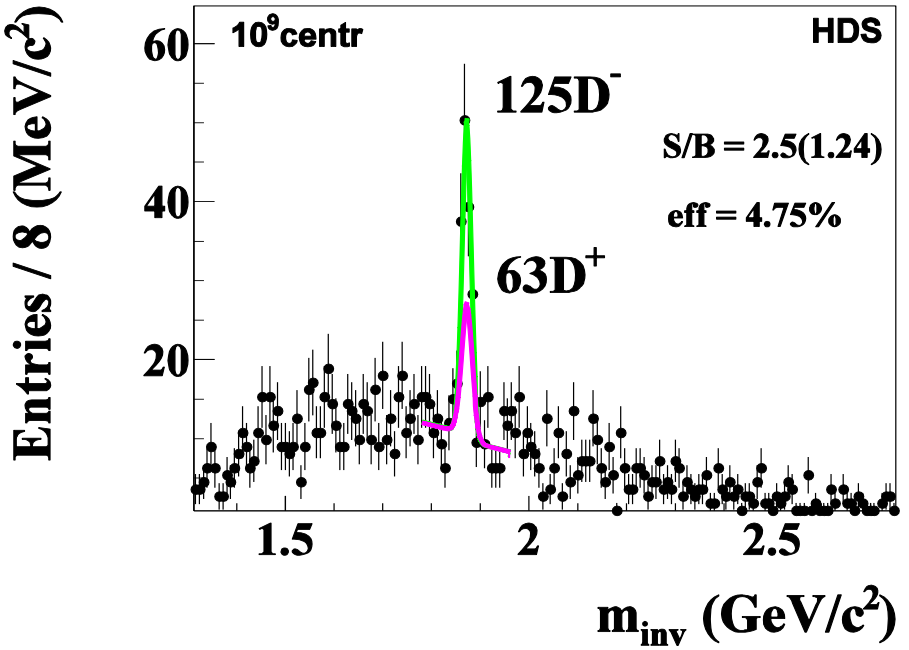
χ^2_{geo}

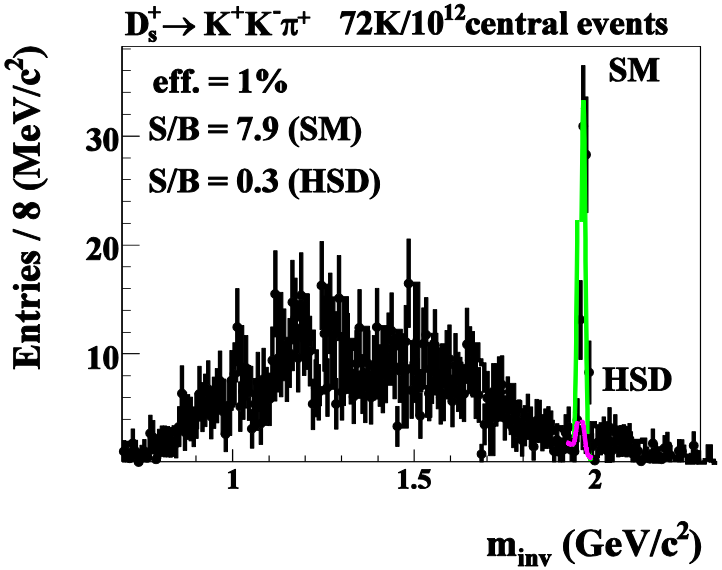


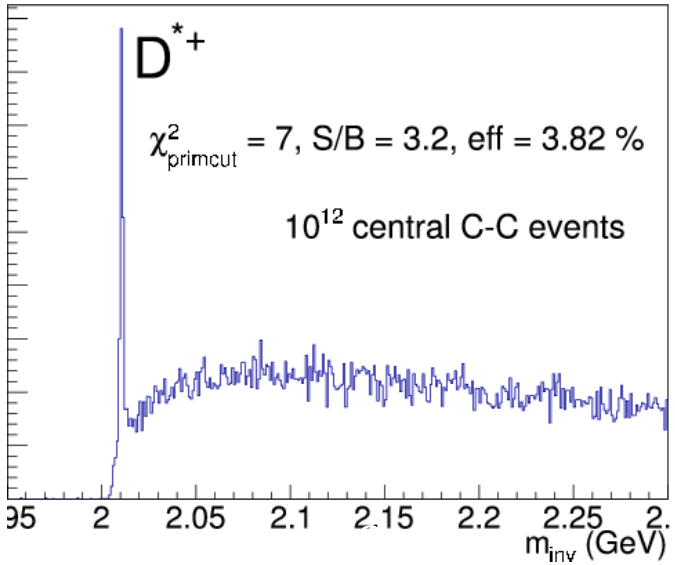


Au+Au @ 25 AGeV


10^10 centr
HSD
1500
1000
500
1.6k
0.6k
D̄0
D0
S/B = 0.5(0.16)
eff = 3.95%
1.5
2
Entries / 8 (MeV/c2)
minv (GeV/c2)


10^9centr
HDS
60
40
20
125D-
S/B = 2.5(1.24)
eff = 4.75%
63D+
1.5
2
2.5
Entries / 8 (MeV/c2)
minv (GeV/c2)


Ds+→ K+K-π+ 72K/10^12central events
eff. = 1%
S/B = 7.9 (SM)
S/B = 0.3 (HSD)
SM
HSD
30
20
10
1
1.5
2
Entries / 8 (MeV/c2)
minv (GeV/c2)


D*+
χ2primcut = 7, S/B = 3.2, eff = 3.82 %
10^12 central C-C events
95
2
2.05
2.1
2.15
2.2
2.25
minv (GeV)

Open charm properties table (25AGeV)

	$\bar{D}^0+D^0$	D^++D^-	D_s^+	Λ_c^+
decay channel	$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^-K^+\pi^+$	$p\,K^-\pi^+$
M_{HSD}	$1.5\cdot10^{-4}$	$4.2\cdot10^{-5}$	$5.4\cdot10^{-6}$	
M_{SM}	$8.2\cdot10^{-4}$	$8.4\cdot10^{-5}$	$1.4\cdot10^{-4}$	$4.9\cdot10^{-4}$
BR(%)	3.8	9.5	5.3	5.0
geo. acc.(%)	29.2	40.1	32.8	71
z-resolution (μm)	52	56	60	69
total eff. (%)	3.95	4.75	1.0	0.05
σ_m (MeV/c^2)	~11	~11	~11	~11
$S/B_{2\sigma}$	0.16/0.5	1.24/2.5	5.0	0.6
Yield/10^{12}mb HSD	14k+41k	47k+89k	0.7k	
Yield/10^{12}mb SHM	78k+225k	95k+179k	19k	3.2 k

CBM timeline

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

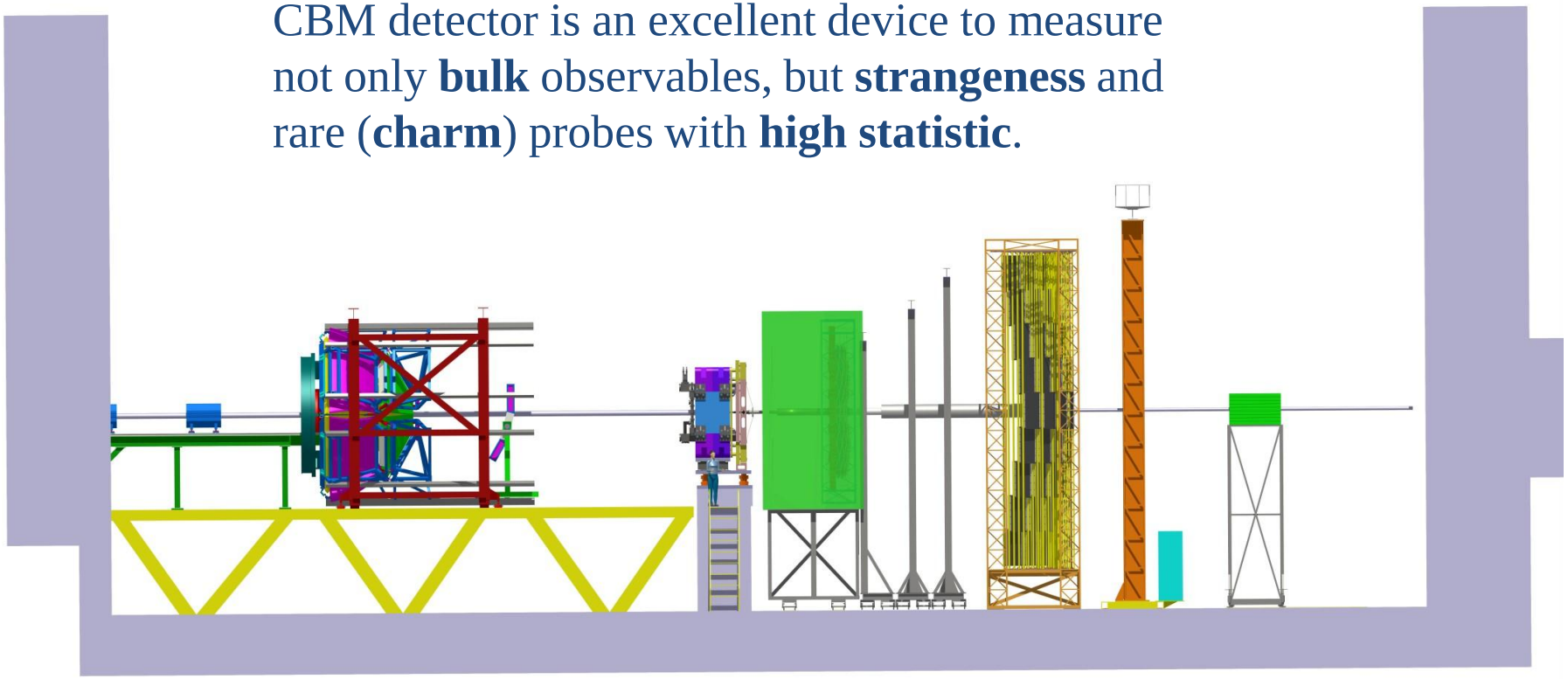
R&D detectors & read-out systems

construction detectors & read-out systems

installation, commissioning

first data taking

CBM detector is an excellent device to measure not only **bulk** observables, but **strangeness** and rare (**charm**) probes with **high statistic**.



he CBM Collaboration: 55 institutions, 450 members

Croatia:
RBI, Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungaria:
KFKI Budapest
Budapest Univ.

Norway:
Univ. Bergen

Germany:
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. KIP
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
Münster Univ.
Tübingen Univ.
Wuppertal Univ.

Korea:
Korea Univ. Seoul
Pusan Nat. Univ.

Romania:
NIPNE Bucharest
Univ. Bucharest

India:
Aligarh Muslim Univ.
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Gauhati Univ.

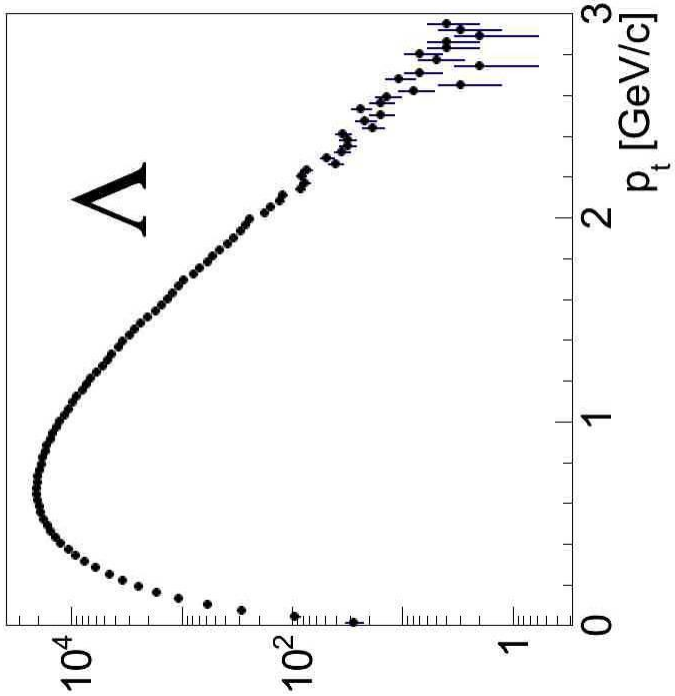
Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.

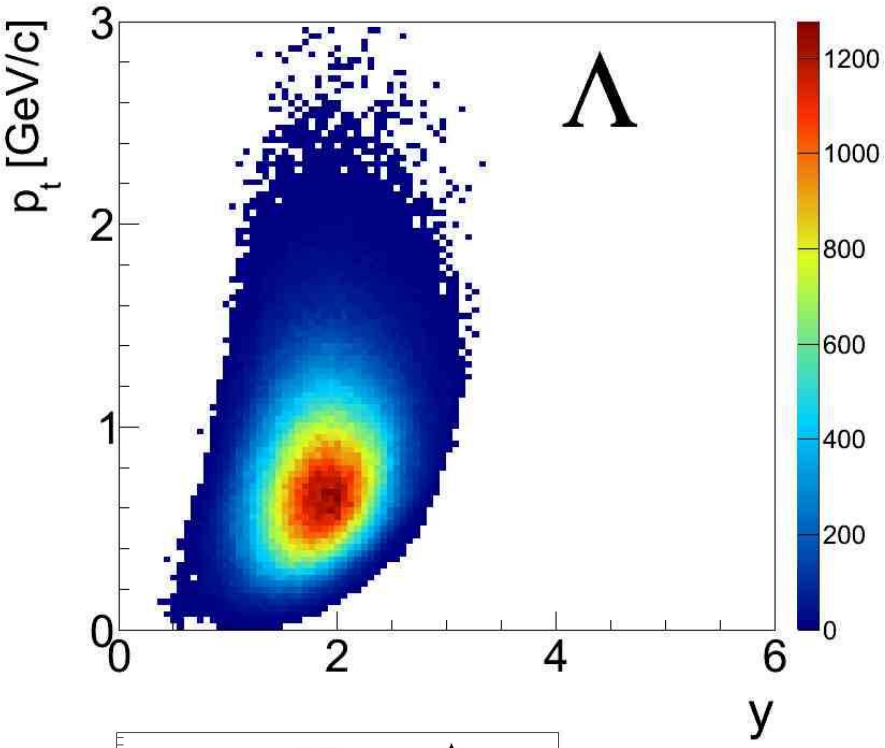
Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

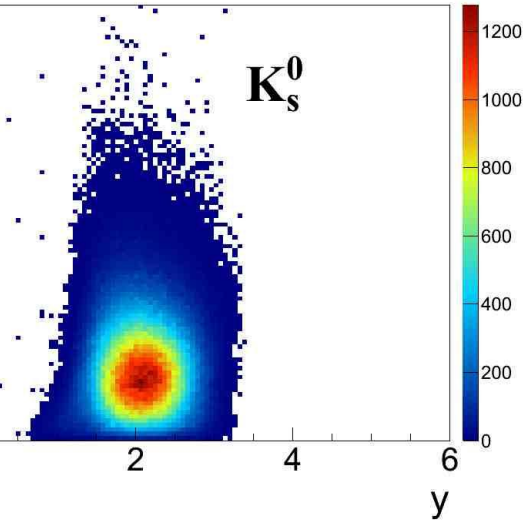
Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

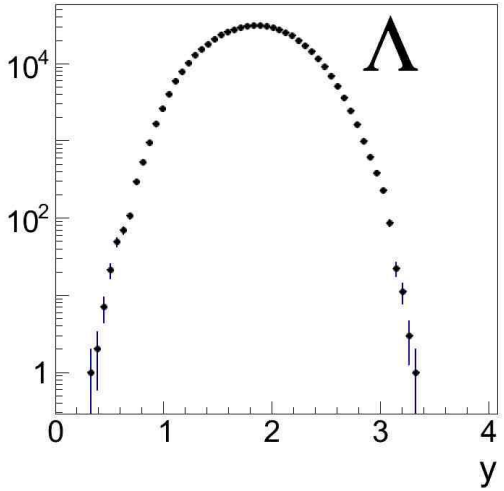
Bulk observables: K^0_s and Λ

170 k central UrQMD events





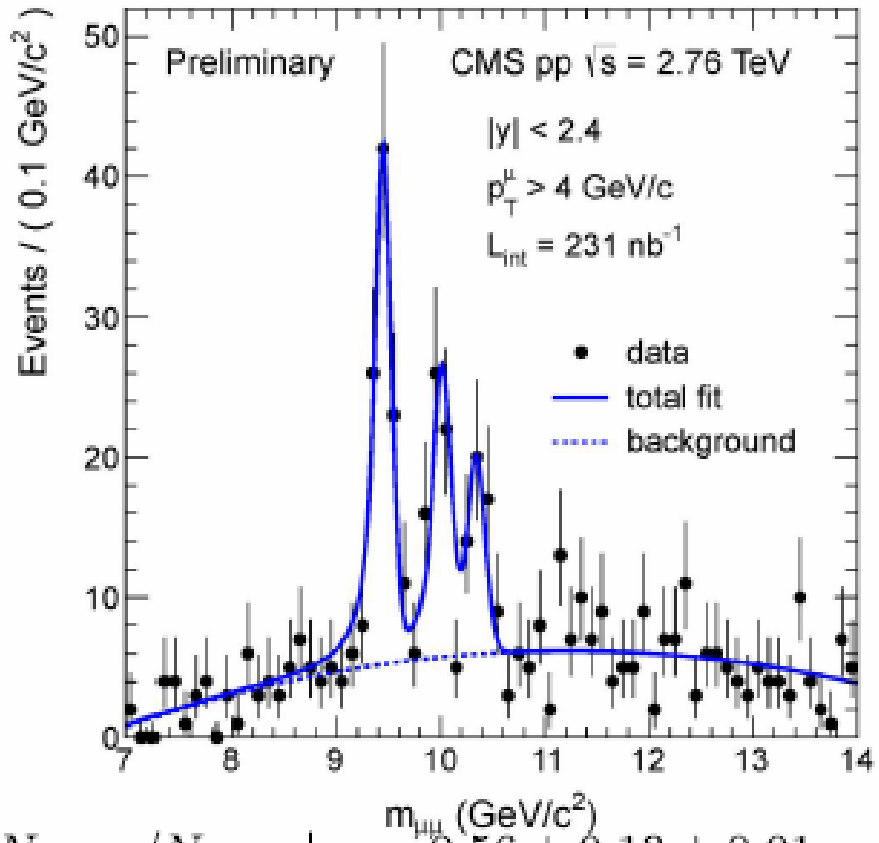




New hard probe at LHC: Upsilon family

Visible difference between states differing only by the binding energy!

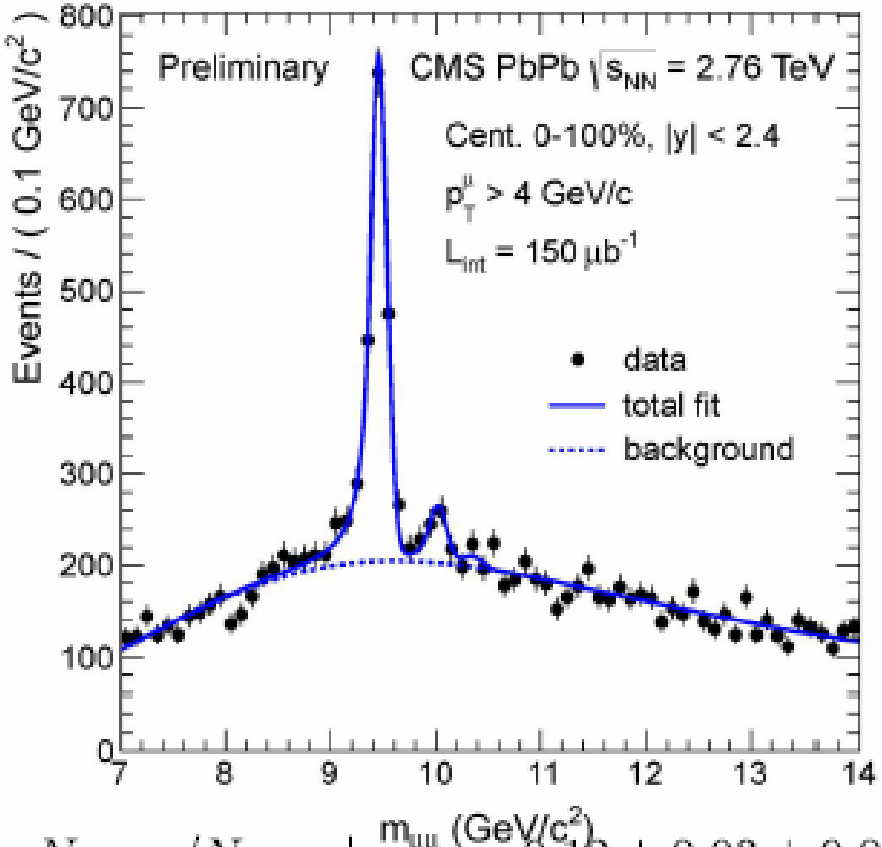
pp



$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

PbPb



$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07 \quad 95\%\ CL$$

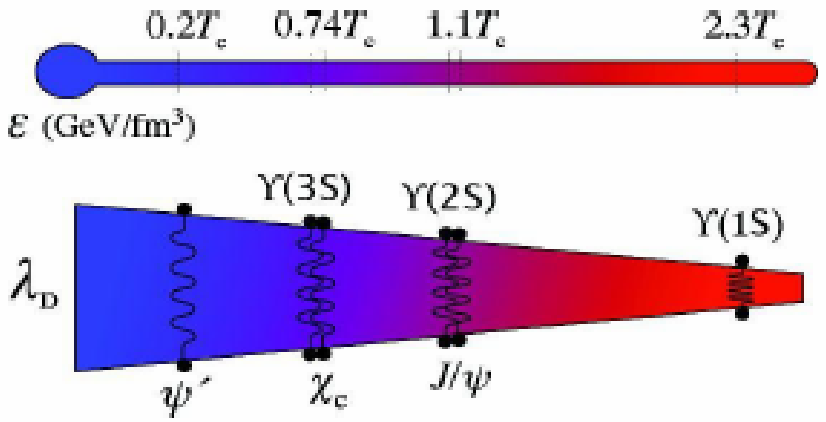
CMS-HIN-11-011

Quarkonia and the QGP

- Heavy quarks
  - produced in the initial hard-scattering process
- Colour screening in QGP leads to melting of quarkonia
- Different binding energy of bound states lead to sequential suppression of states with increasing temperature

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



Matsui & Satz
PLB 178 (1986) 416