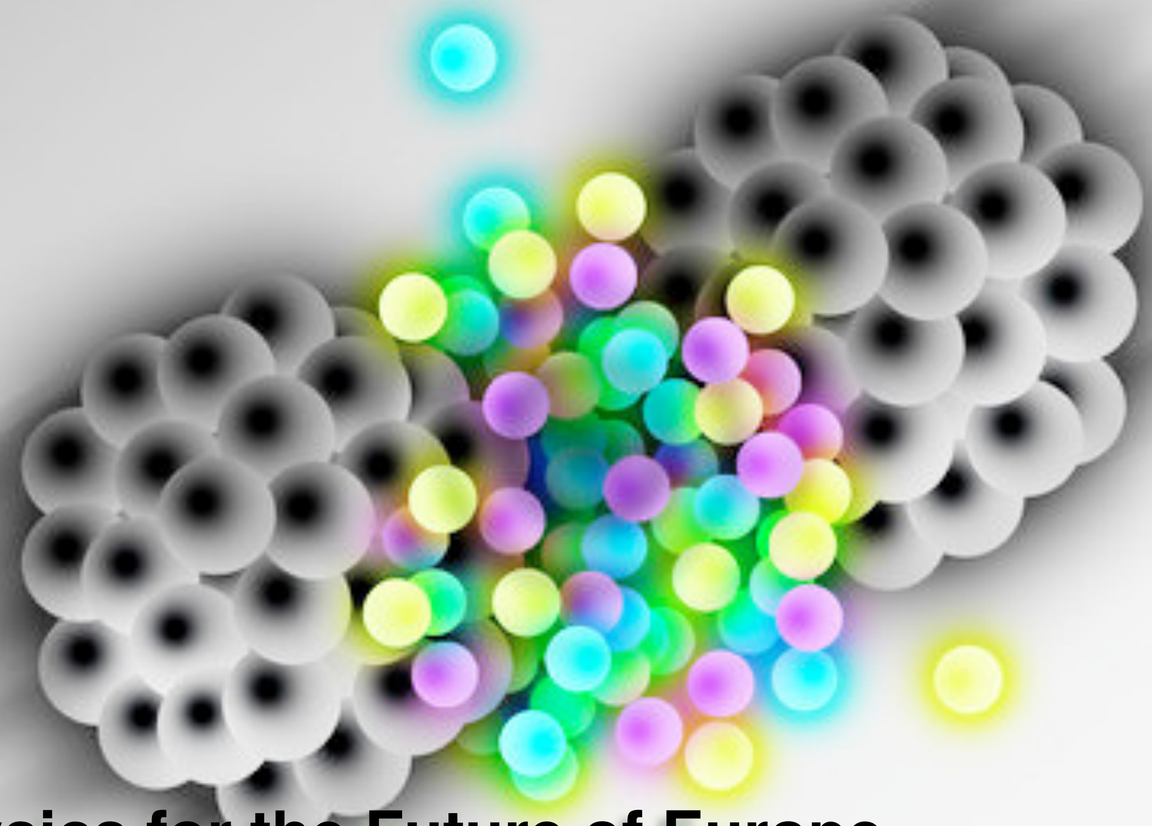
Fixed target & Heavy-Ions

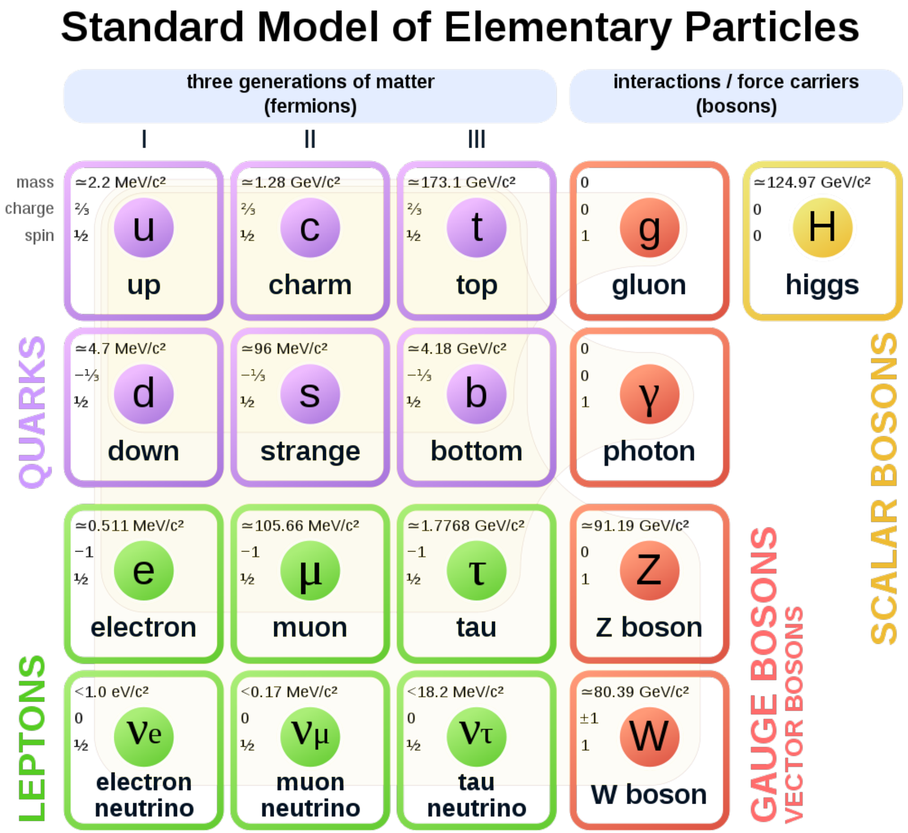


Liliana Apolinário

Particle Physics for the Future of Europe

Monday, Sep 28th, IST

SM & QCD



Quantum ChromoDynamics

QCD coupling: $\alpha_s(Q^2)$

High-Energy ⟵ ⟶ Low-Energy

Asymptotic freedom

Precision physics for high-energy colliders

QCD Factorization

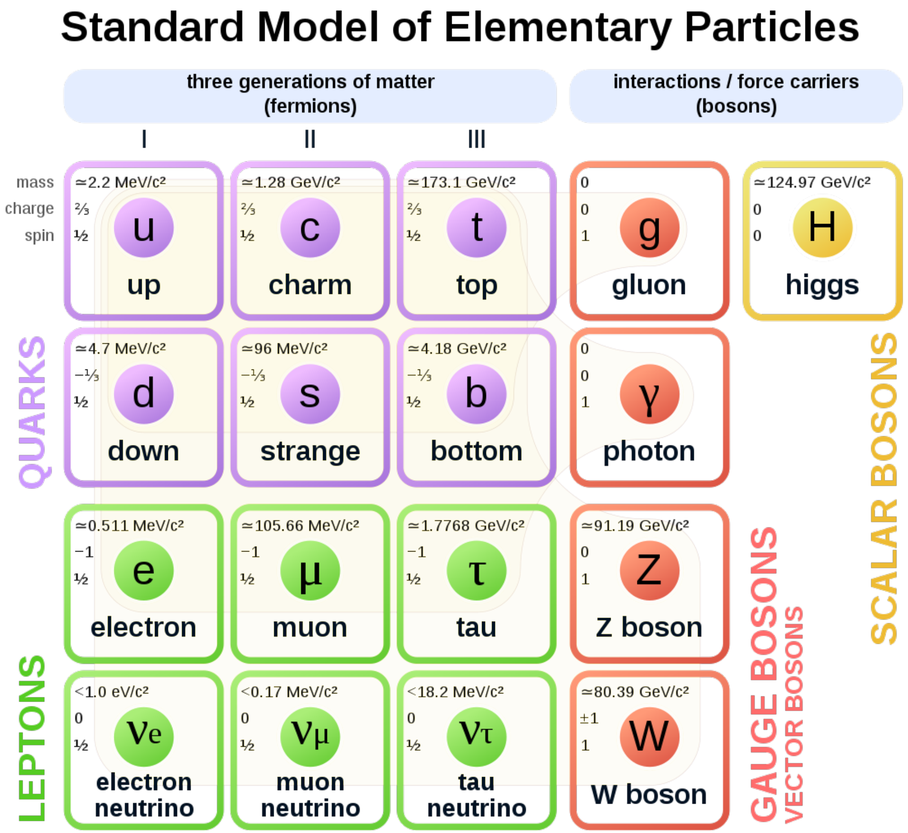
Confinement

(??)

QCD Phenomenology

Form Factors, PDFs, Hadronisation models,….

SM & QCD



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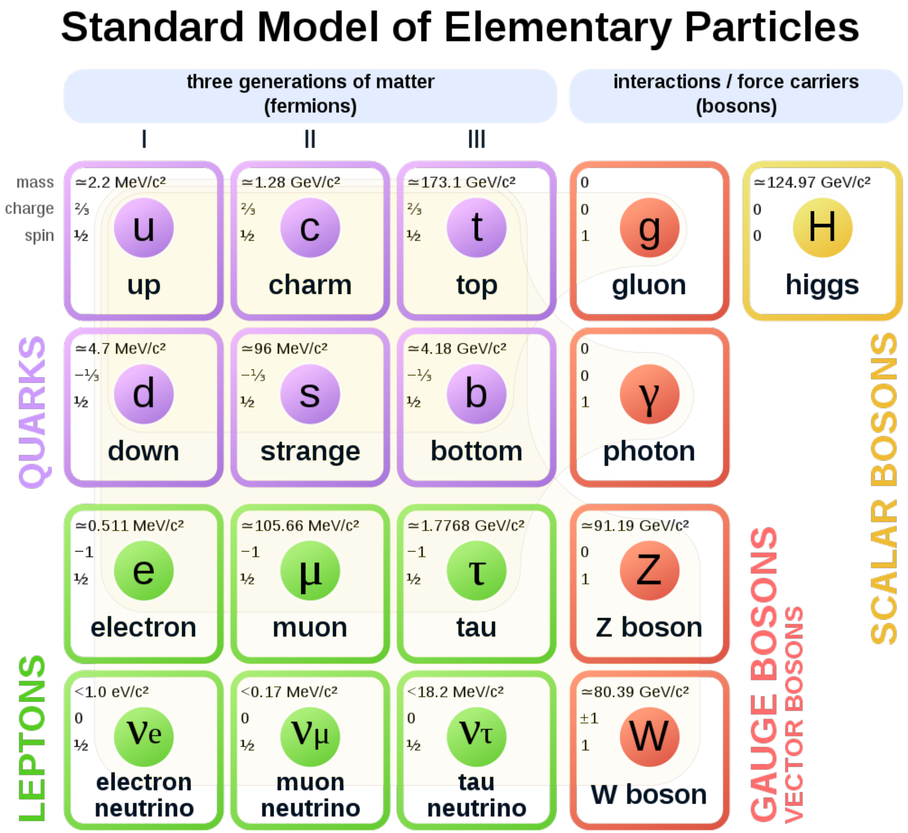
Fundamental objects of investigation

Input to predictions

SM & QCD



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Confinement

(??)

QCD Phenomenology

Form Factors, PDFs, Hadronisation models,….

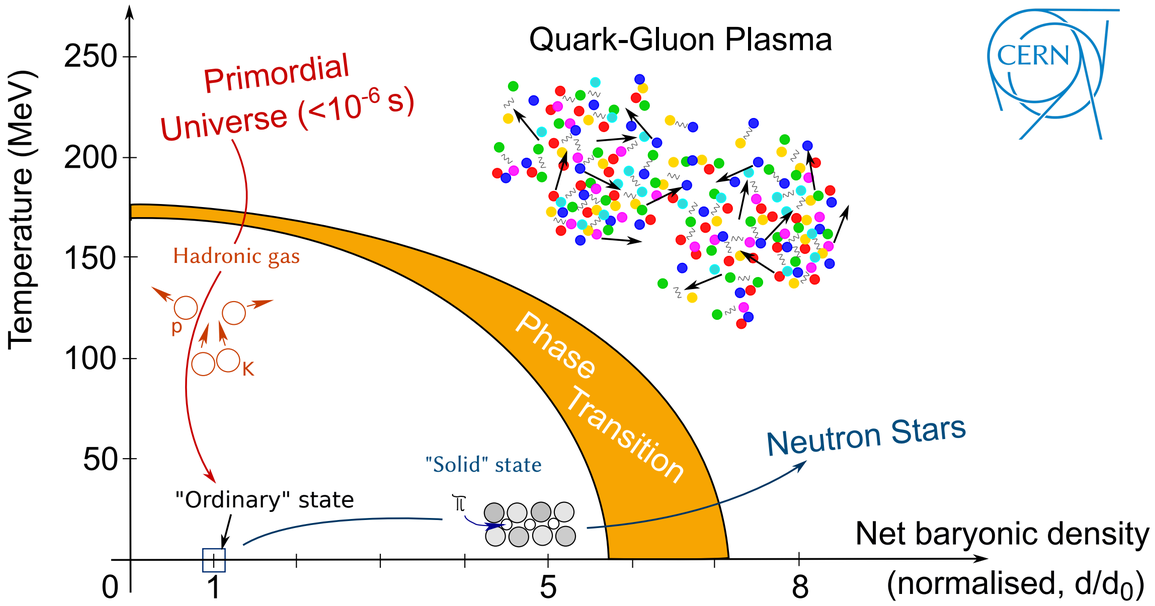
Fundamental objects of investigation

Input to predictions

Precision era of Electroweak and Higgs physics demand a new level of QCD understanding

QCD program at future pp, ep DIS, e^+e^- would be highly beneficial

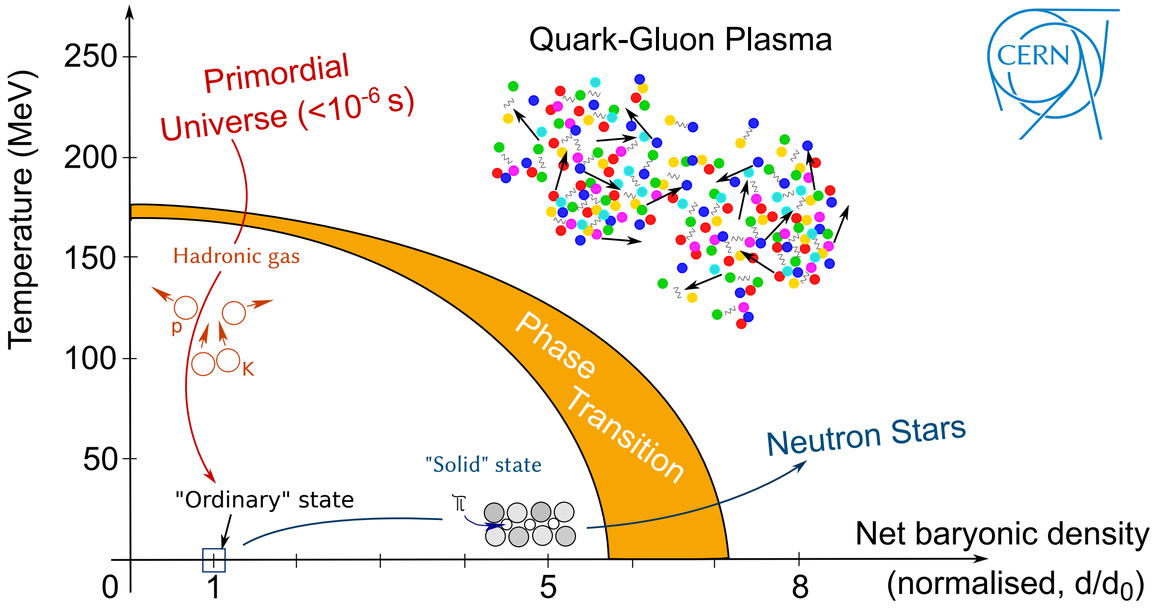
Quark Gluon Plasma



QCD High-temperature can be experimentally accessed in the lab:

Quark-Gluon Plasma

Quark Gluon Plasma



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Nuclear beams physics program:

Emergence of high collectivity phenomena from microscopic laws of QCD

QGP @	*Soft Sector*	*Hard sector*
AA		

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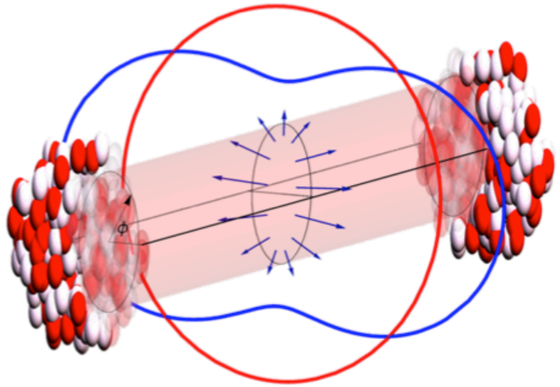

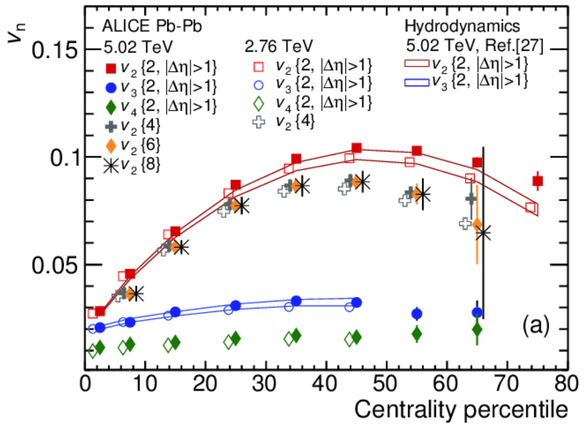

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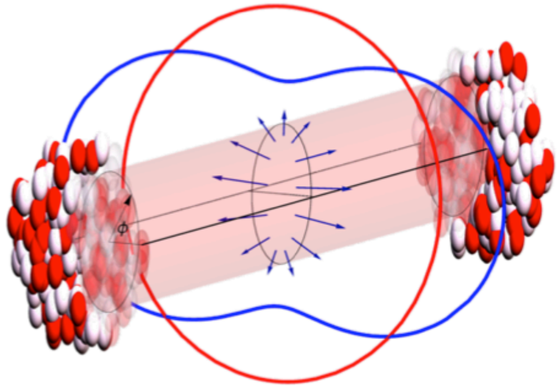

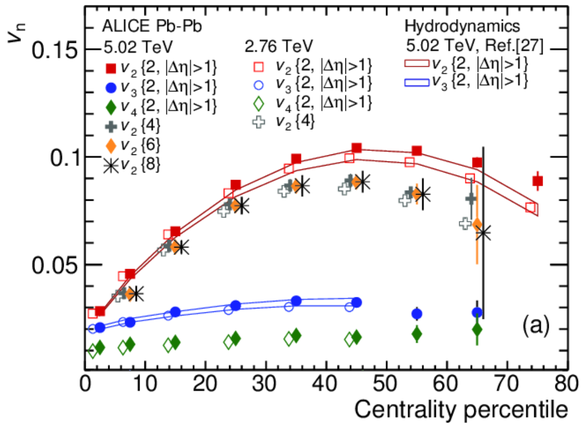

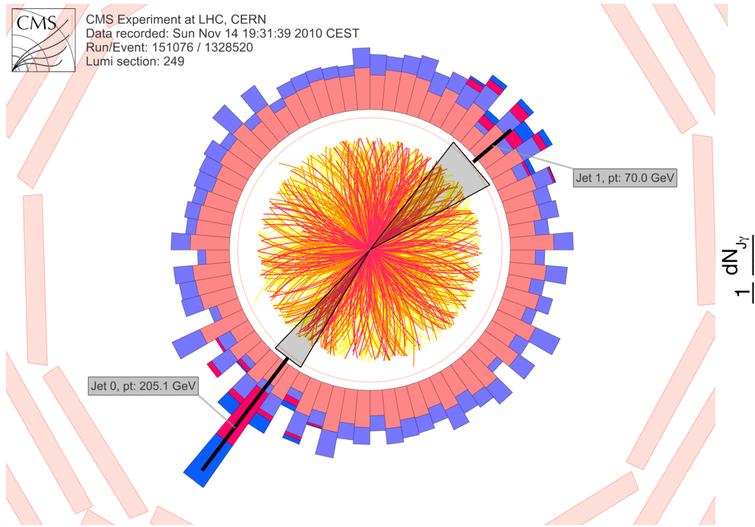

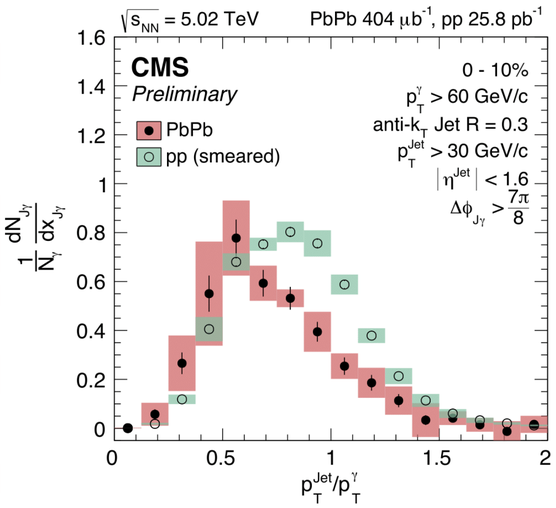

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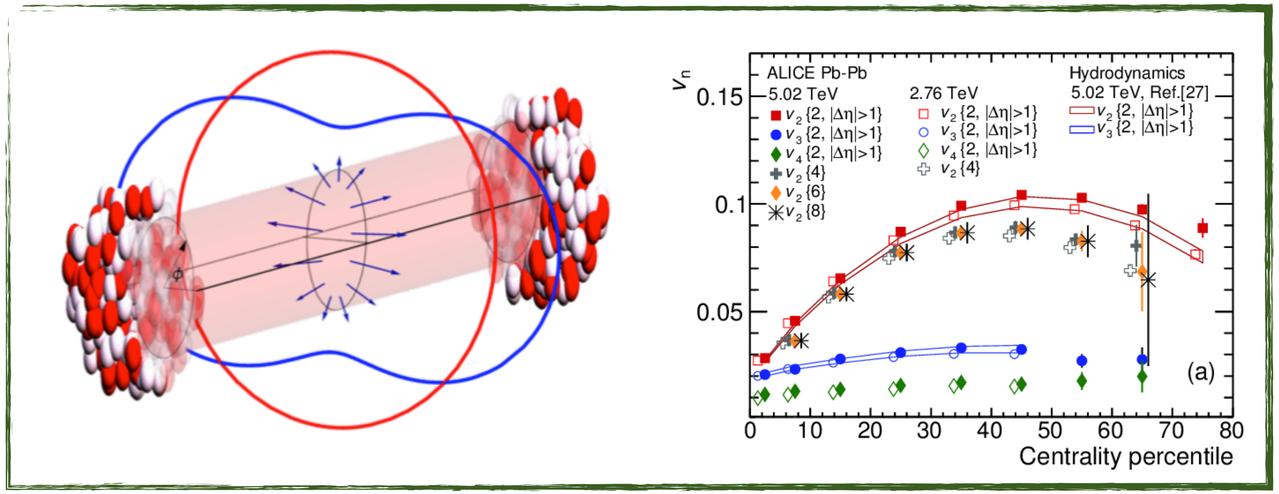

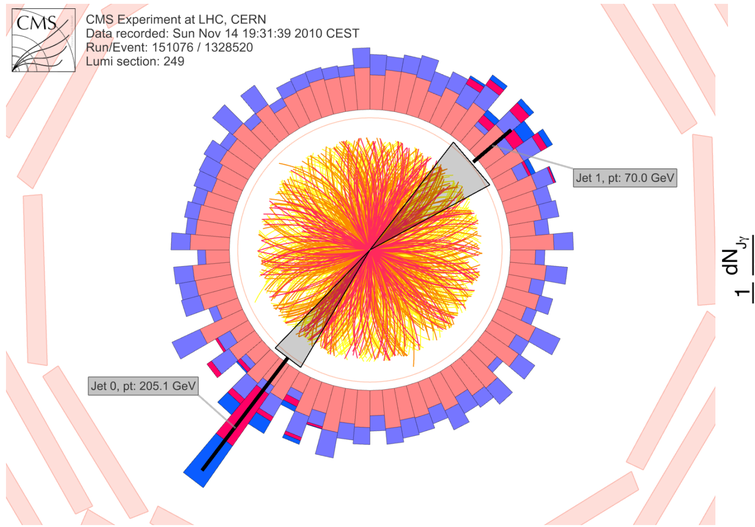

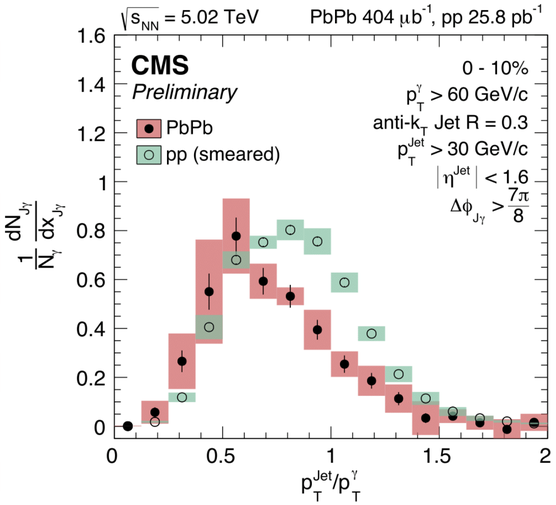

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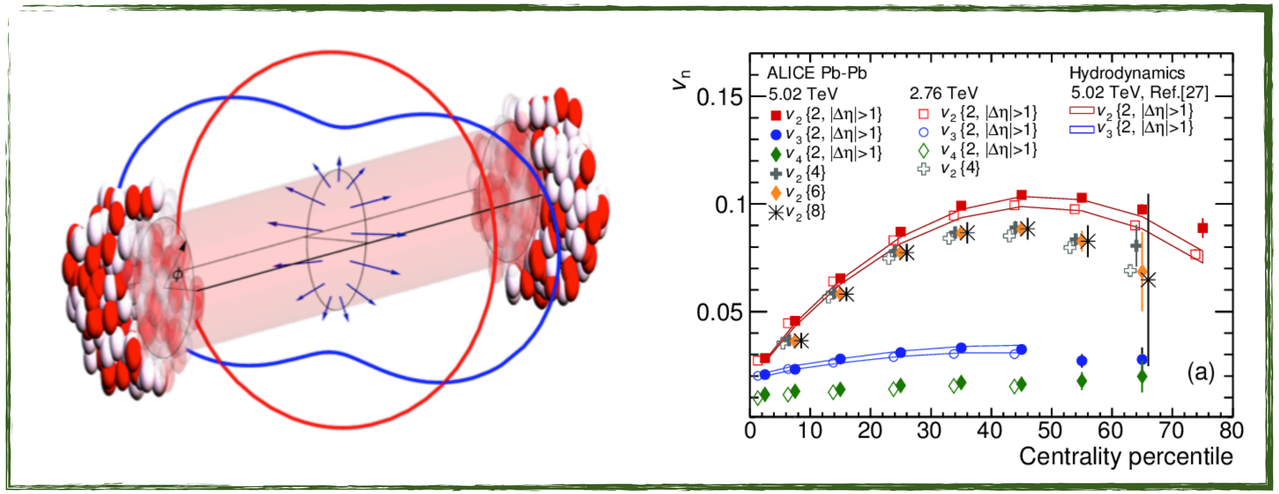
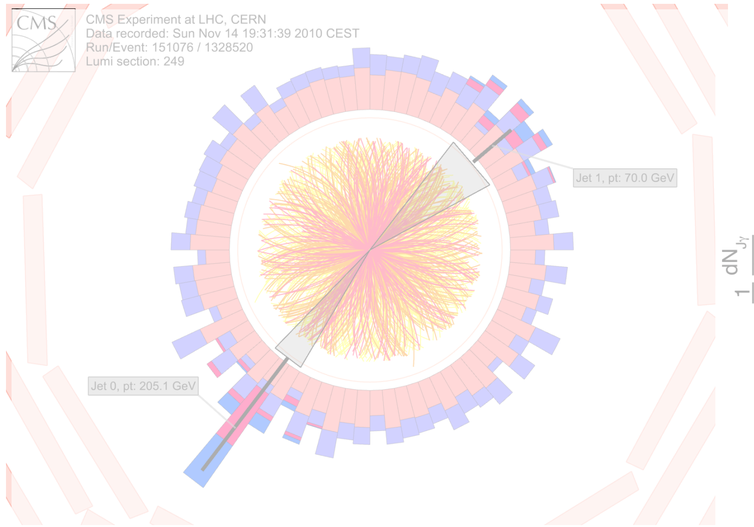
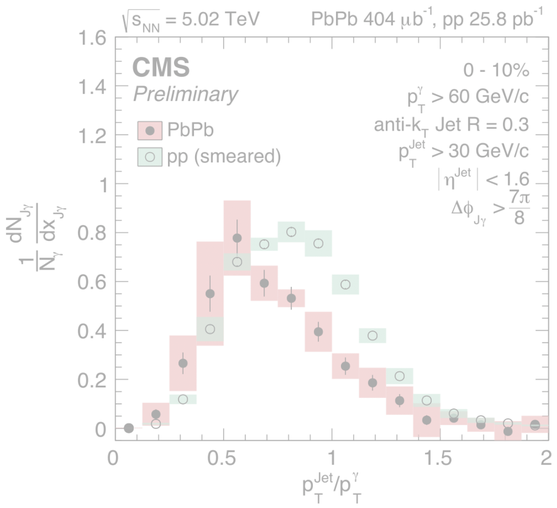
pA and pp	✓	

With LHC - Run 2

Quark Gluon Plasma







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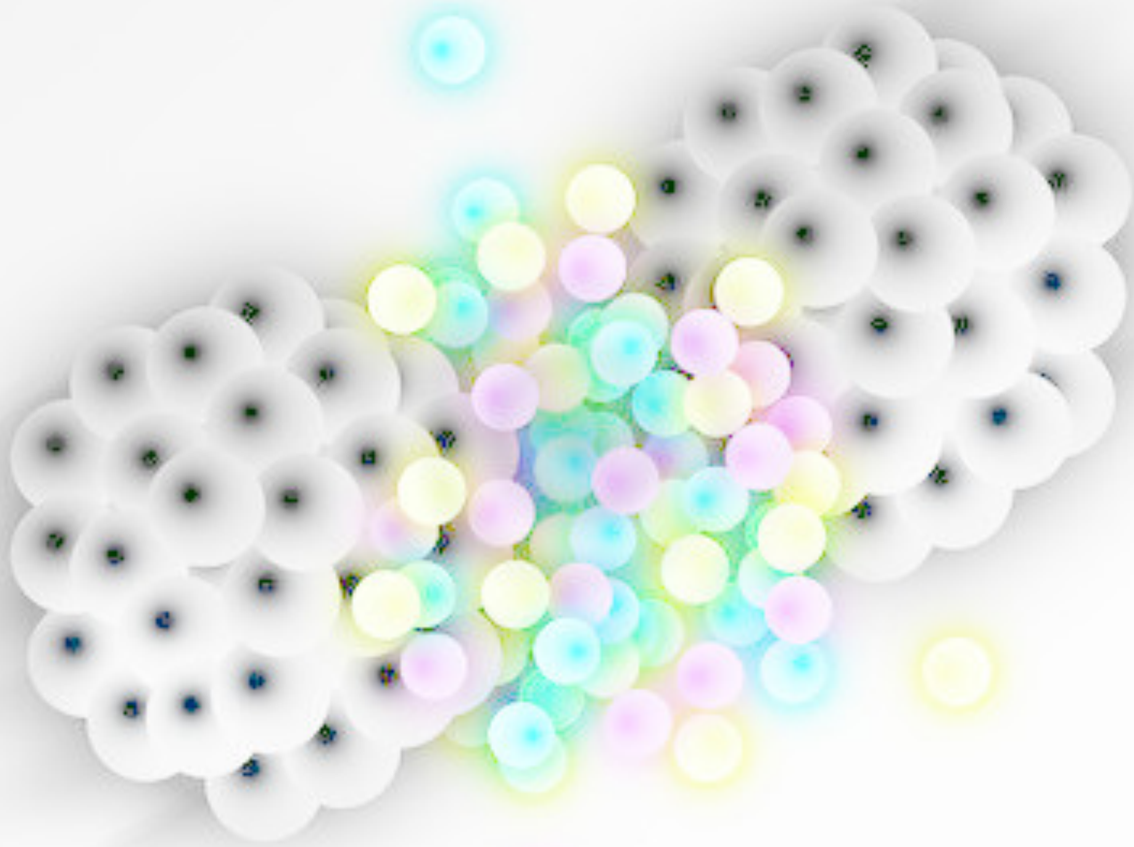
AA	✓	✓
pA and pp	✓	**??**

With LHC - Run 2

Future experimentation with nuclear beams:

Experimentally test how equilibrium properties arise in a non-Abelian QFT

Opportunities and Challenges @ LHC



Opportunities and Challenges @ LHC

Proposed Run Schedule

all to be read as +1 year

	Year	Systems, time, L_{int}	Total per Run (3 and 4)
RUN 3	2021 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.2/nb ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE O-O: 500/μb p-O: 200/μb
	2022 (6 weeks)	p-O + O-O 7 TeV, 1 week (after EYETS?) Pb-Pb 5.5 TeV, 5 weeks	
	2023 (4 weeks)	pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks	
	LS3	ATLAS/CMS upgrades, ALICE: ITS3? FoCal?	
RUN 4	2027 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.8/nb, ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE
	2028 (6 weeks)	Pb-Pb 5.5 TeV, 2 weeks p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days	
	2029 (4 weeks)	Pb-Pb 5.5 TeV, 4 weeks	
	LS4		
RUN 5		Intermediate A-A, 11 weeks pp reference, 1 week	E.g. Ar-Ar 3-9/pb (optimal species to be defined)

This is a proposal agreed in WG5 and reflects the physics discussed in the YR. The final run schedule is decided by the LHCC upon discussion with the experiments.

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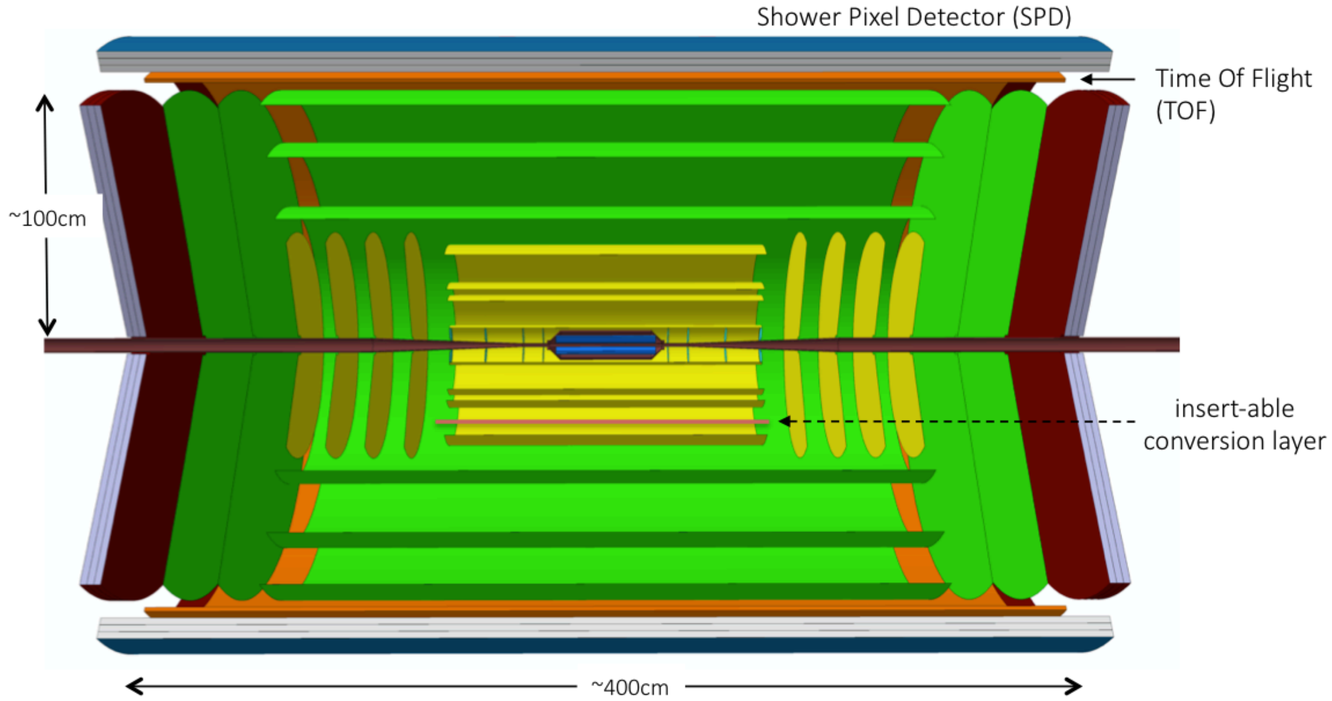
[Adamová et al:1902.01211]

Detector Upgrade [an example]

- Compact, next-generation multi-purpose detector at the LHC as a follow-up to the present **ALICE** experiment

Designed for :

- pp, pA and AA collisions
- Luminosities 20 to 50 higher than ALICE detector (upgraded for LS2 and LS3)



CMS and ATLAS with similar efforts

[Adamová et al:1902.01211]

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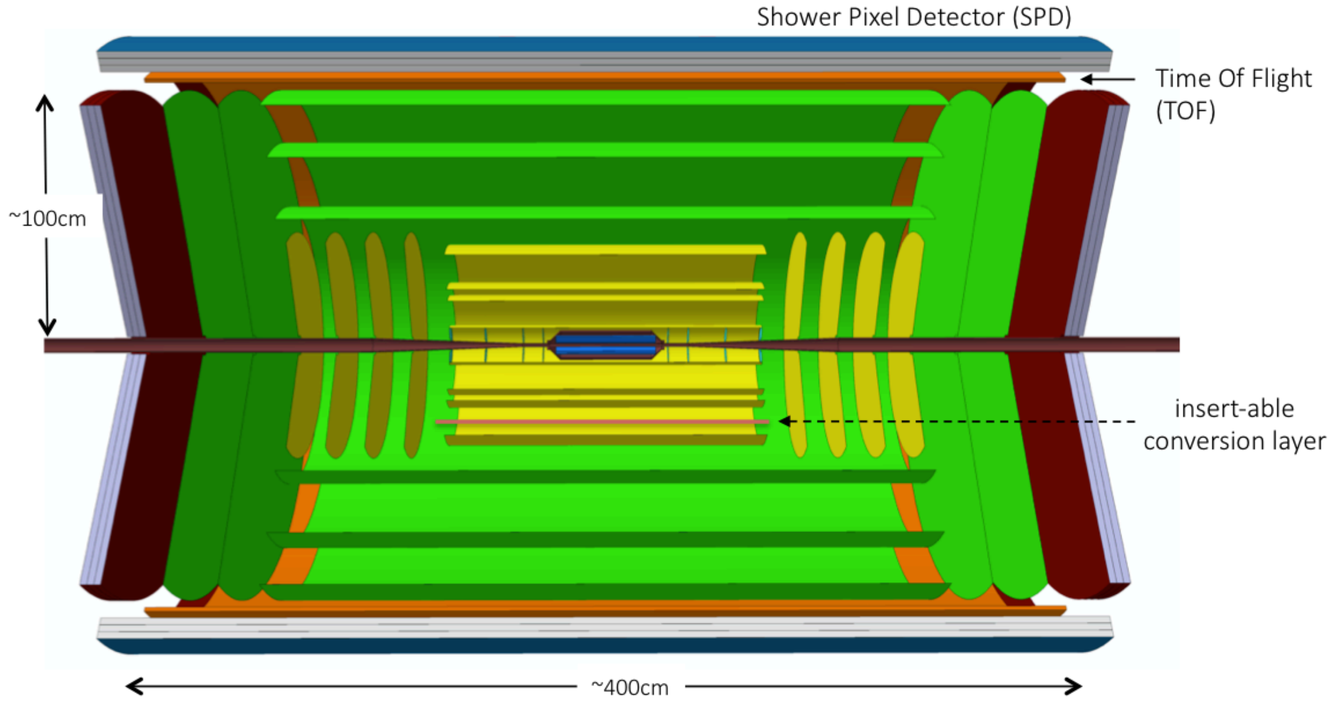
Rich physics program:

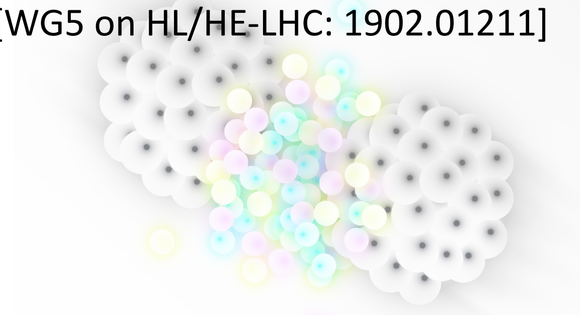
- Heavy flavour and quarkonia
- Low-mass dileptons ($0 < m < 3$ GeV)
- Chiral Symmetry Restoration
- Soft and ultra-soft photons ($1 < p_T < 100$ MeV)

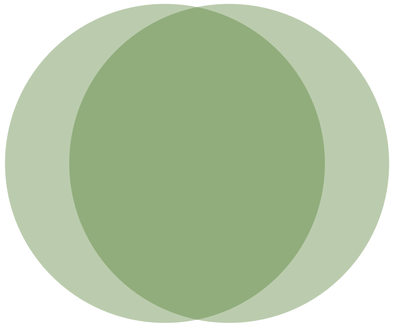


CMS and ATLAS with similar efforts

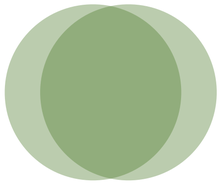
[WG5 on HL/HE-LHC: 1902.01211]

Light Ions





Pb
A = 206

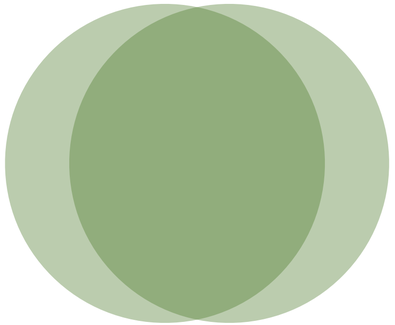


Ar, ??
A = 40, ??

- ⇧ Volume and Lifetime
  - ⇧ Temperature
  - ⇧ Multiplicity

[WG5 on HL/HE-LHC: 1902.01211]

Light Ions



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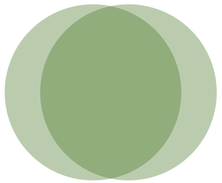

Ar, ??
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⇩ QGP effects

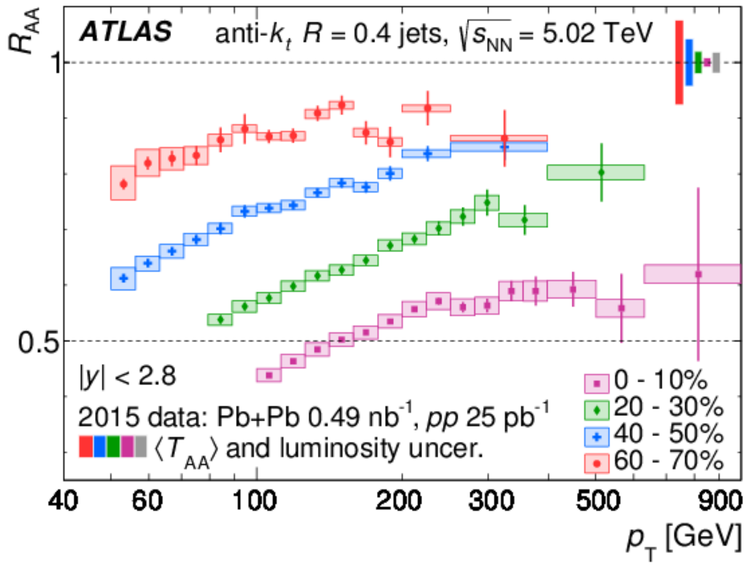
⇧ Volume and Lifetime

⇧ Temperature

⇧ Multiplicity

$\langle N_{\text{part}} \rangle \sim 70$

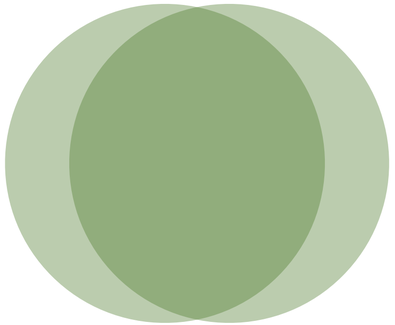
0-10% ArAr ⟷ **40-50% PbPb**



QGP effects experimentally confirmed

[WG5 on HL/HE-LHC: 1902.01211]

Light Ions



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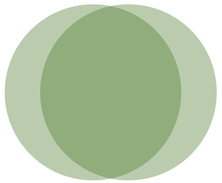

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⇩ Background: **higher precision/ accuracy**

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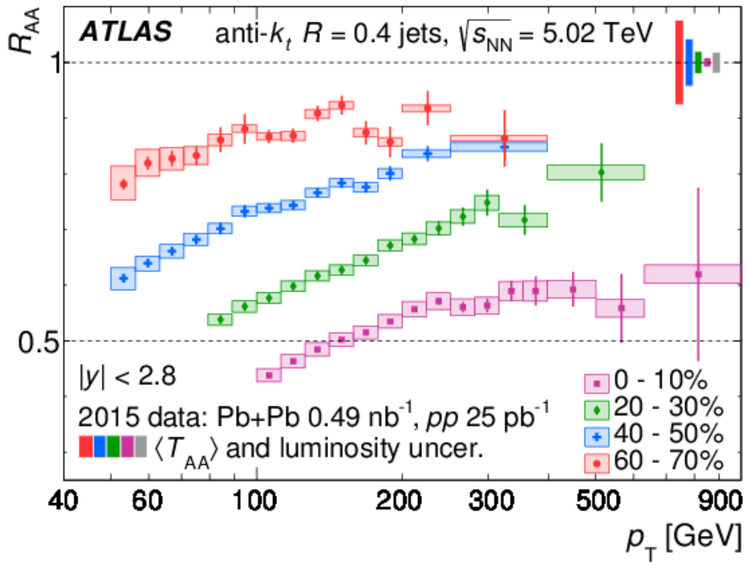

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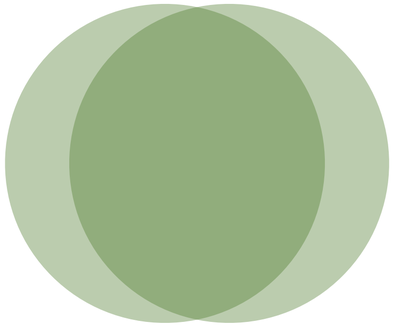

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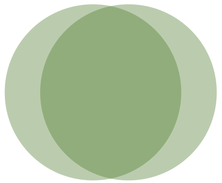

Ar, ??
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⇩ QGP effects

⇩ Background: **higher precision/ accuracy**

⇧ Volume and Lifetime

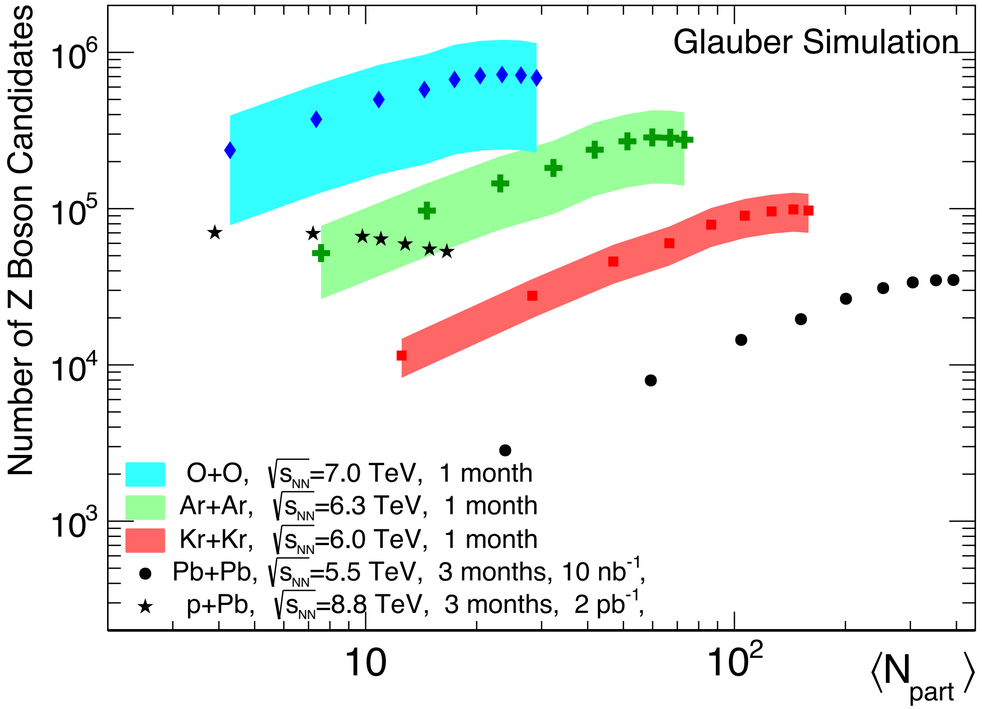
⇧ Temperature

⇧ Multiplicity

⇧ Luminosity (Production Rate): **unlock rare probes** (Z+jet, ttbar,…)

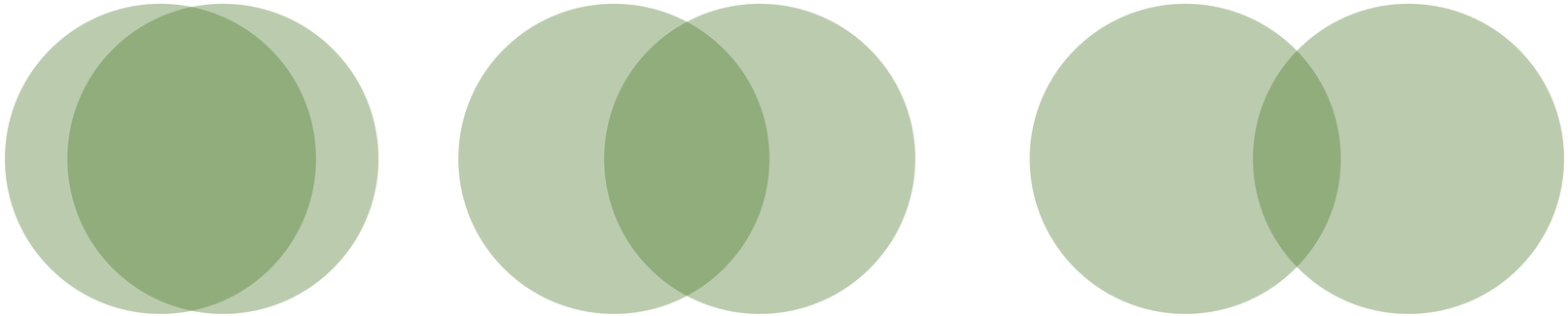
$$\mathcal{L}_{NN}^{ArAr} = [8; 25] \times \mathcal{L}_{NN}^{PbPb}$$

~ order of magnitude increase in number of hard processes



[WG5 on HL/HE-LHC: 1902.01211]

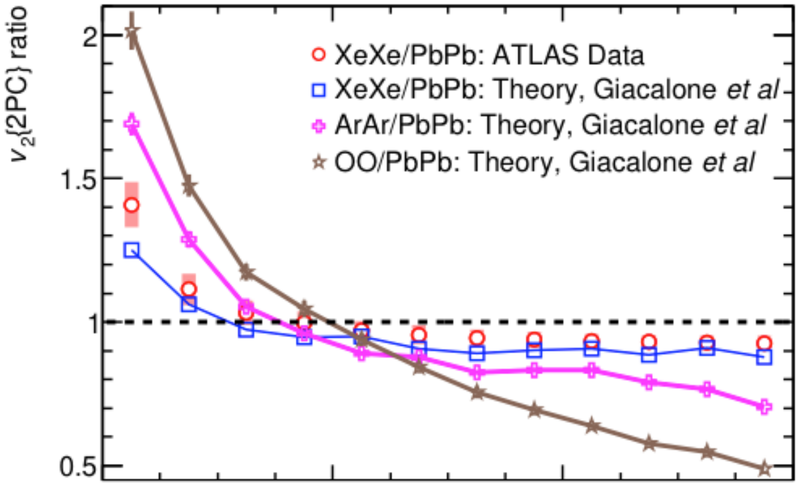
System size dependence



Pb Pb Pb

Studies of System Size dependence

Flow Coefficients based on strong variation of spatial eccentricity of nuclear overlap



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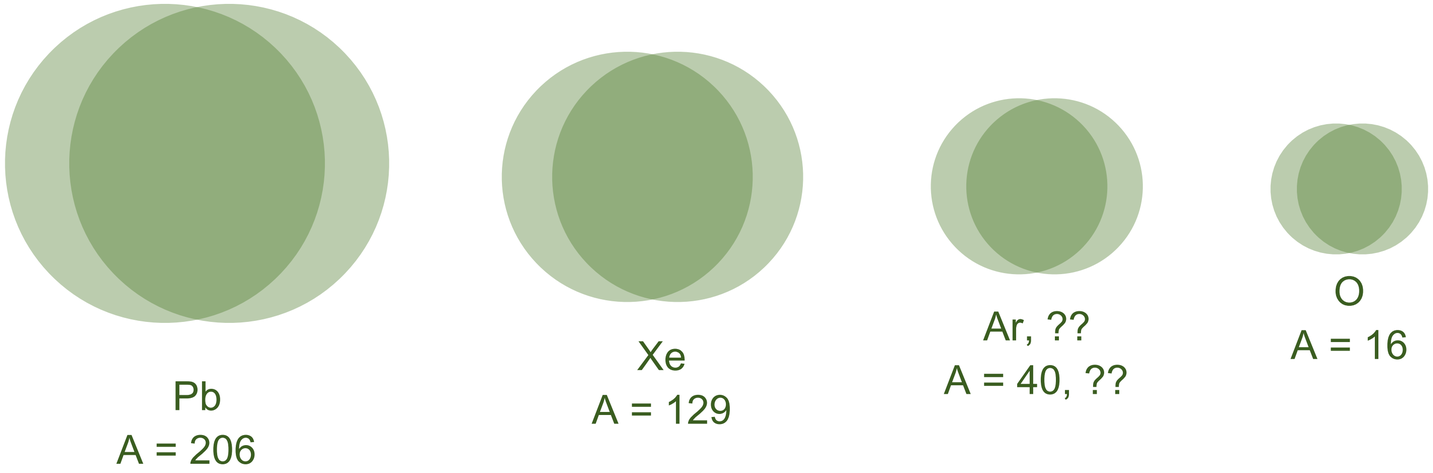
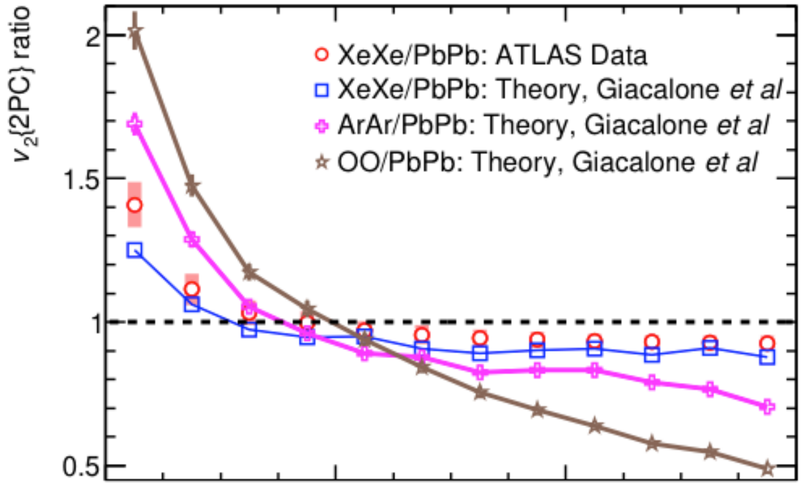


Studies of System Size dependence
(always fixing geometry - [0-10]%)

Better control on initial condition to collectivity studies

Fixing centrality and varying overall size allows for disentanglement of event-averaged eccentricity from its event-by-event fluctuations



Future Opportunities and Challenges

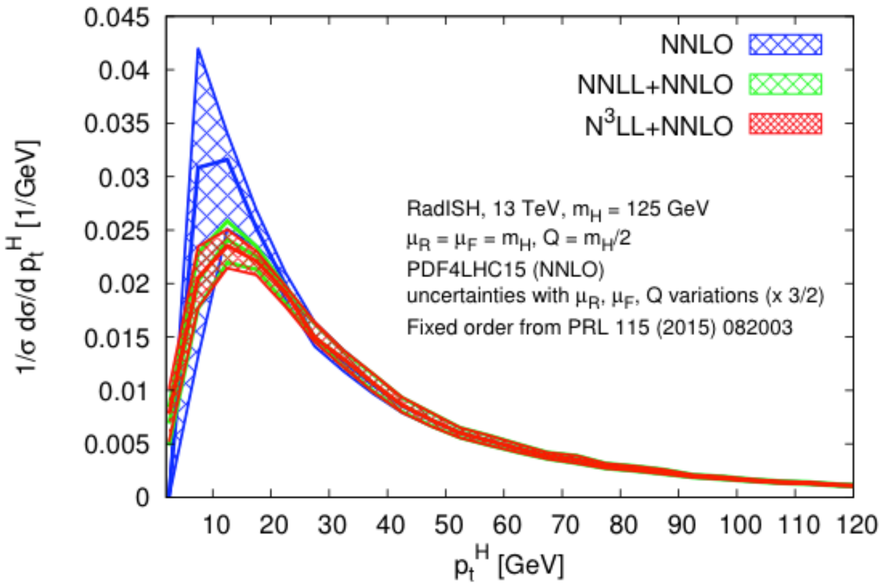
Towards a Future hadronic collider

QCD Precision studies

[CERN-ACC-2018-0045]

[W. Bizoń et al (18)]

- Accessible at $e^+ + e^-$, p+p, p+h,…
  - QCD Coupling constant: $\alpha_s(Q^2)$



Least-known coupling of the SM with a large impact:

Collinear factorisation (PDFs, FF, Hadronisation), Lattice calculations, pQCD at NnLO,…

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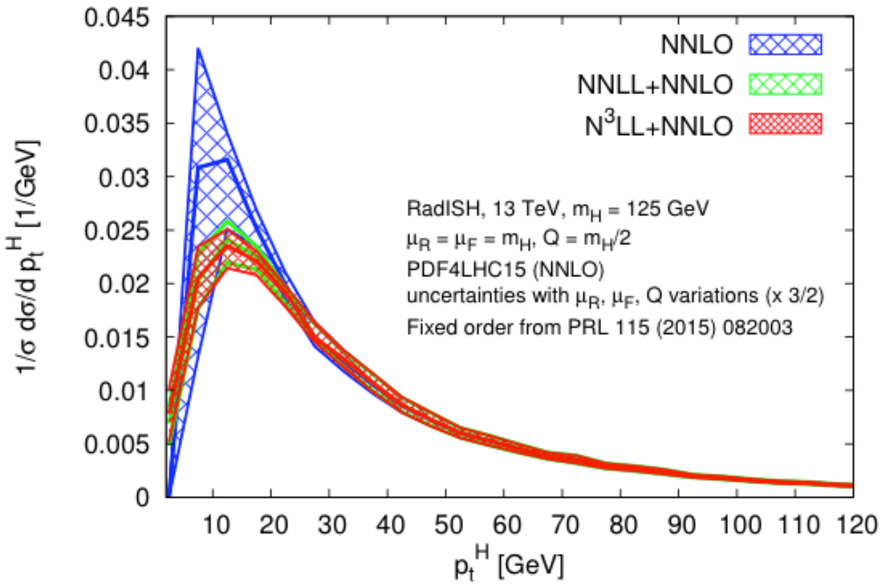
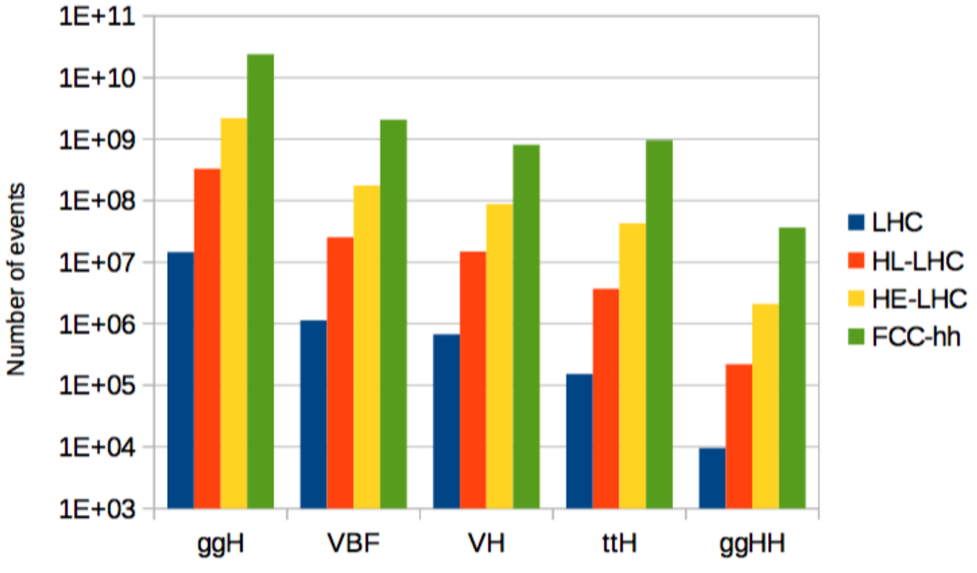
Least-known coupling of the SM with a large impact:
Collinear factorisation (PDFs, FF, Hadronisation), Lattice calculations, pQCD at NnLO,…

  - Highly-boosted dijets, multijets, pentaquarks and other exotic hadron structures,…
  - non-pQCD (color reconnection, hadronisation,…)





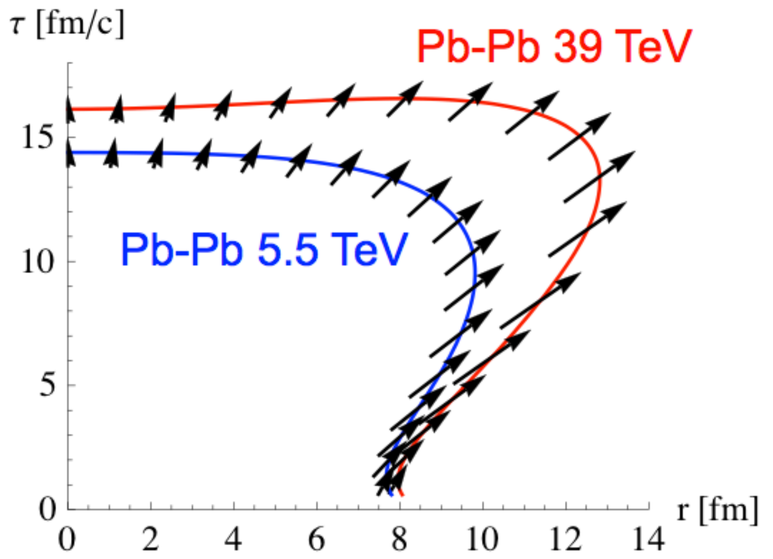
QGP Bulk properties

[FCC-CDR Vol1]

- Future hadronic accelerator will bring a larger/denser/hotter and long-lived medium:

Quantity	Pb–Pb 5.5 TeV	Pb–Pb 10.6 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	2000	2400	3600
$dE_T/d\eta$ at $\eta = 0$	2.3–2.6 TeV	3.1–3.4 TeV	5.2–5.8 TeV
Homogeneity volume	6200 fm^3	7400 fm^3	11000 fm^3
Decoupling time	11 fm/c	11.5 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	16–17 GeV/fm^3	22–24 GeV/fm^3	35–40 GeV/fm^3

~ x 2 w.r.t LHC



Expected impact on medium bulk proprerties:

- Denser medium ⇒ longer expansion and larger volume (before freeze-out)
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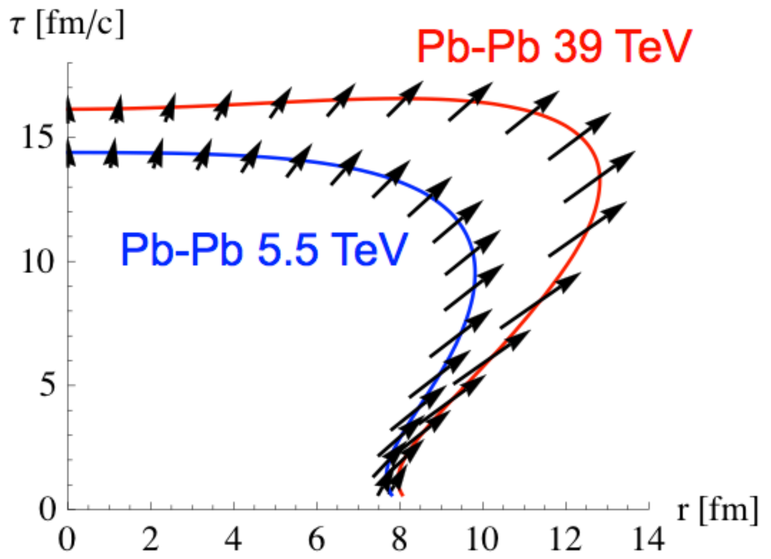

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Novel Qualitative features:

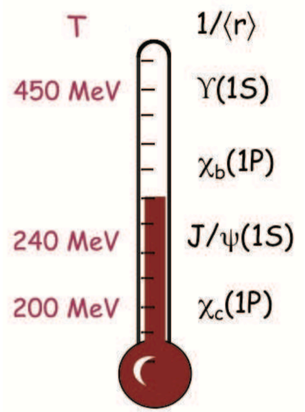
- Thermal charm production
- Dependence of the QCD EoS with quark masses (larger d.o.f)

Unlock Novel probes of the QGP:

- W/Z + jet, ttbar events
- Novel features on J/ψ and Y states

Quarkonia

[Liu et al (09), Zhao et al (11), Andronic et al, 11]
[FCC-CDR Vol1]



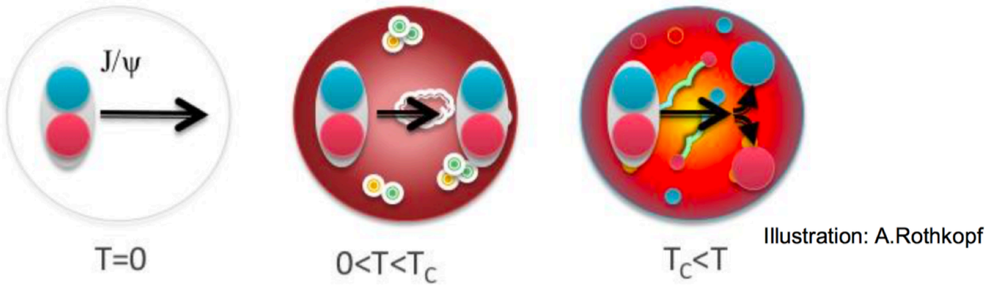


Illustration: A.Rothkopf

Quarkonia production in the QGP:

- Sequential melting (can be used as a thermometer)

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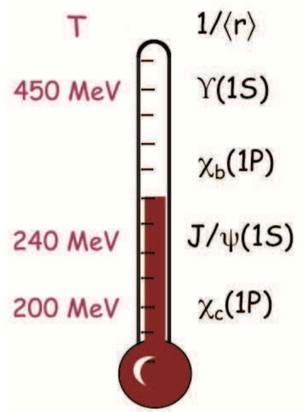

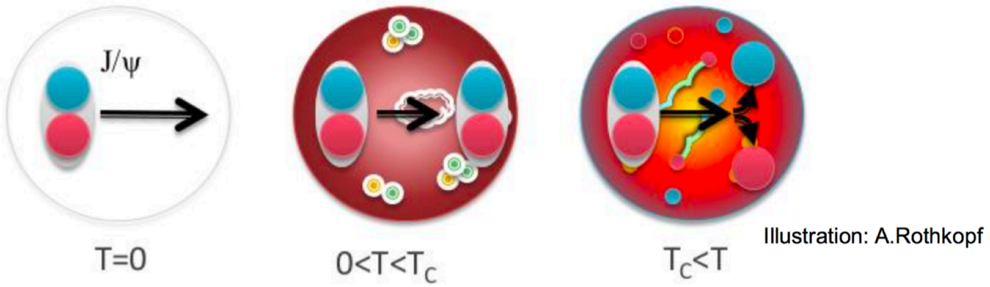

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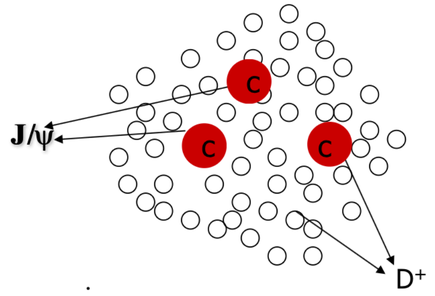

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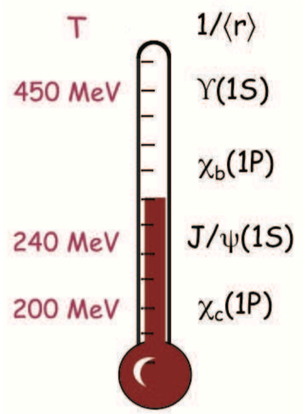

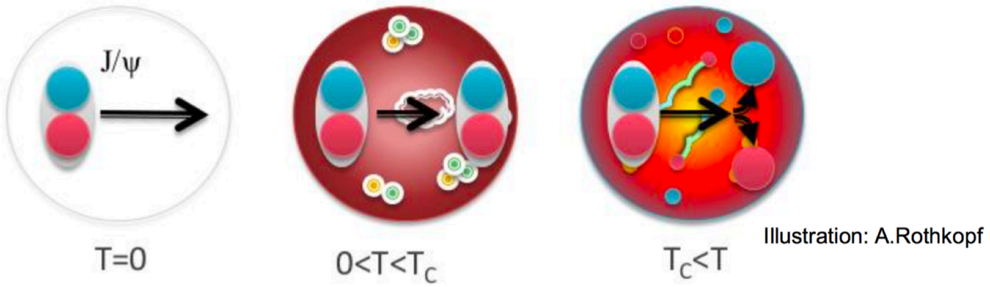

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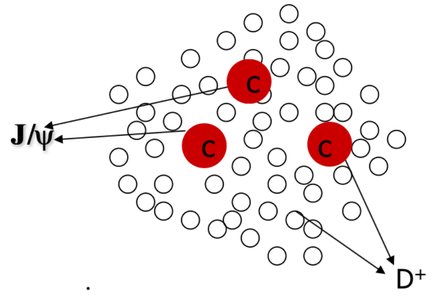
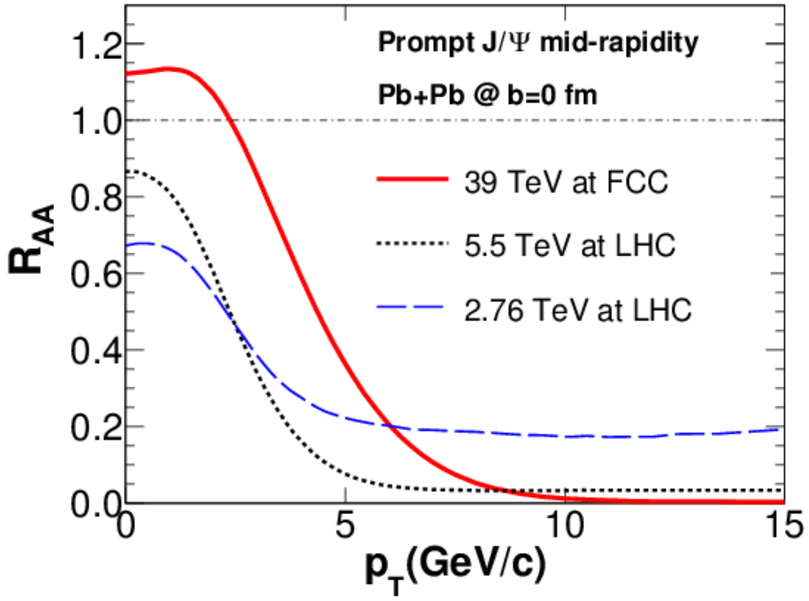


Striking evidence of cc recombination



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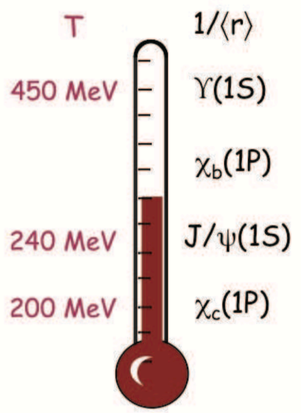

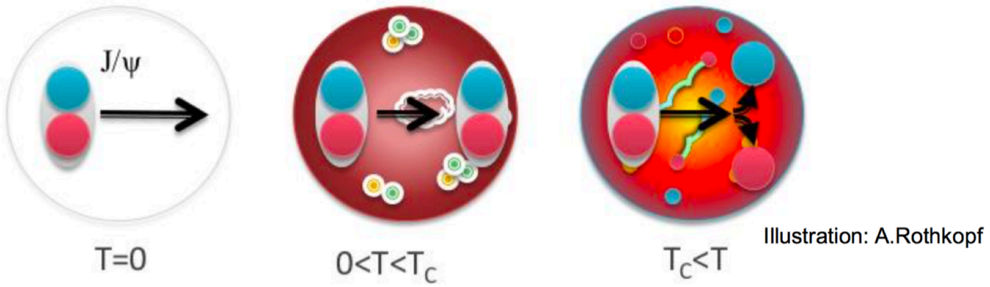

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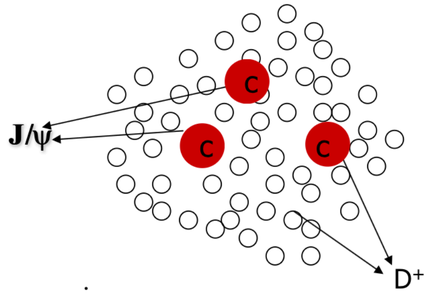

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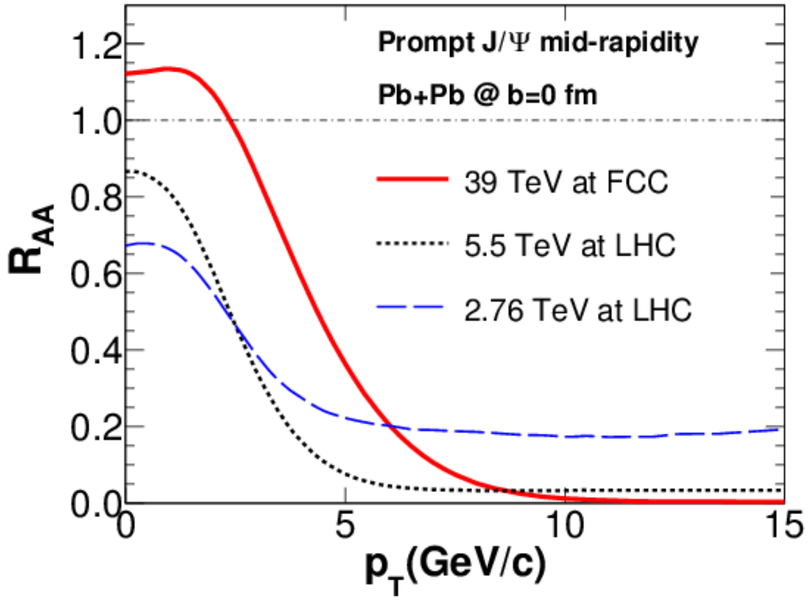
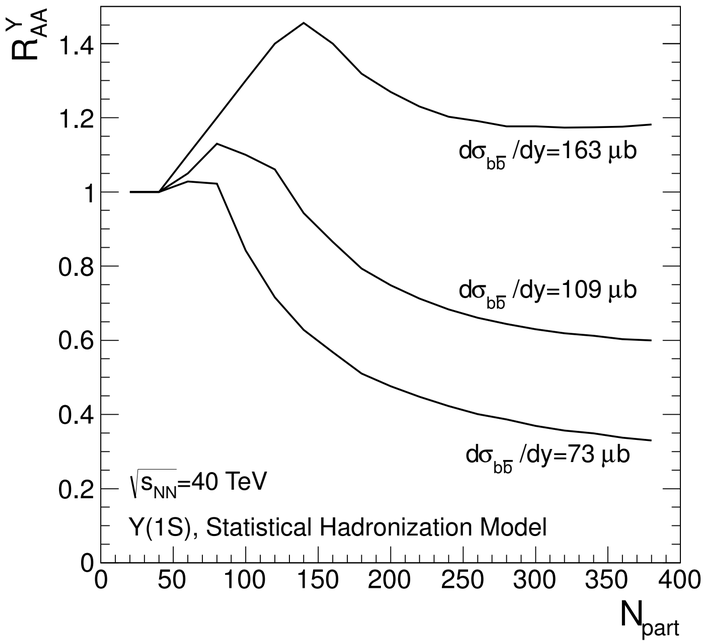
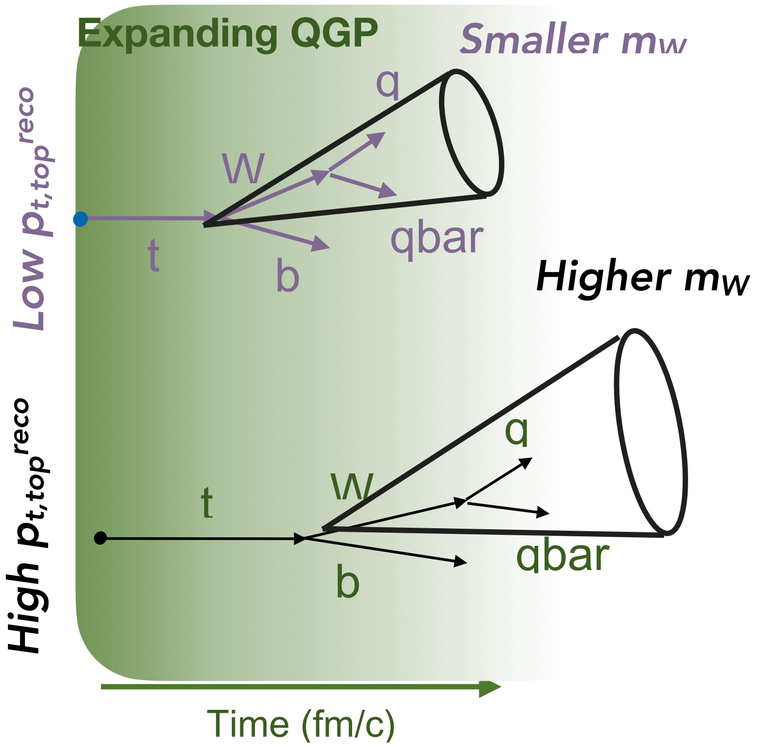




Possible suppression of the tightly bound state of Y(1S)

Jet quenching

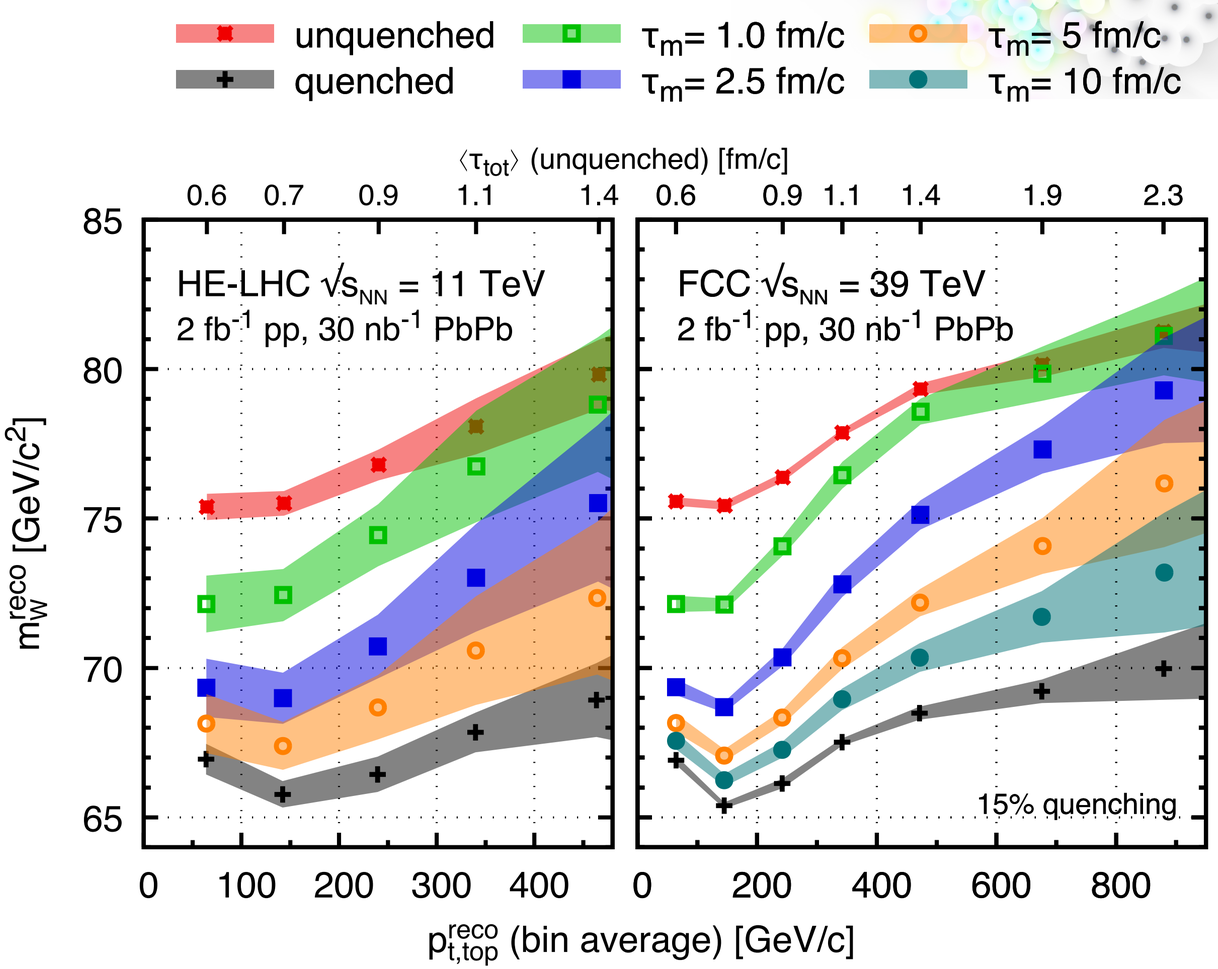
[LA, Milhano, Salam and Salgado (18)]
[FCC-CDR Vol1]



Reconstructed W mass: m_W

Will depend on the energy that is lost

(medium length that jet is able to "see")



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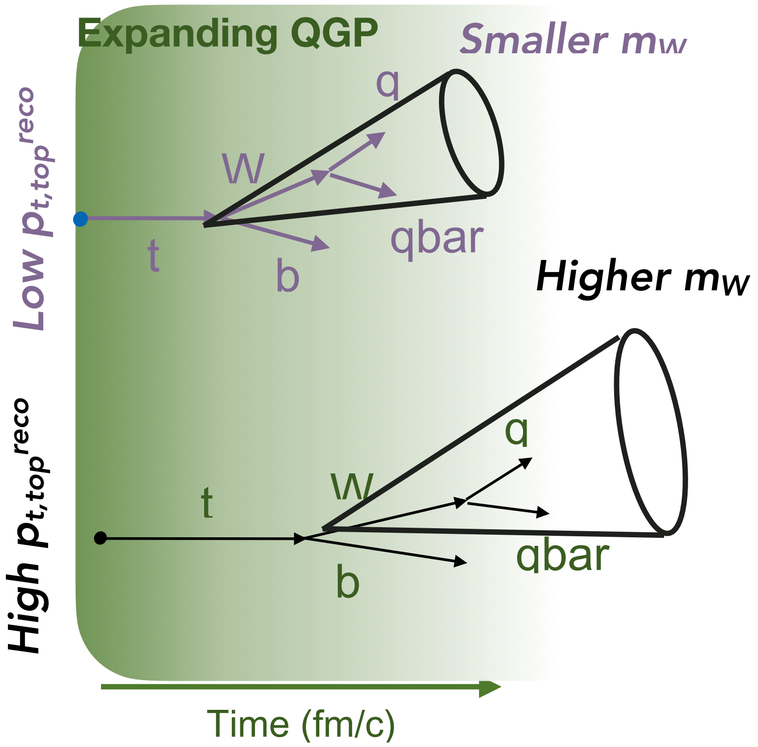

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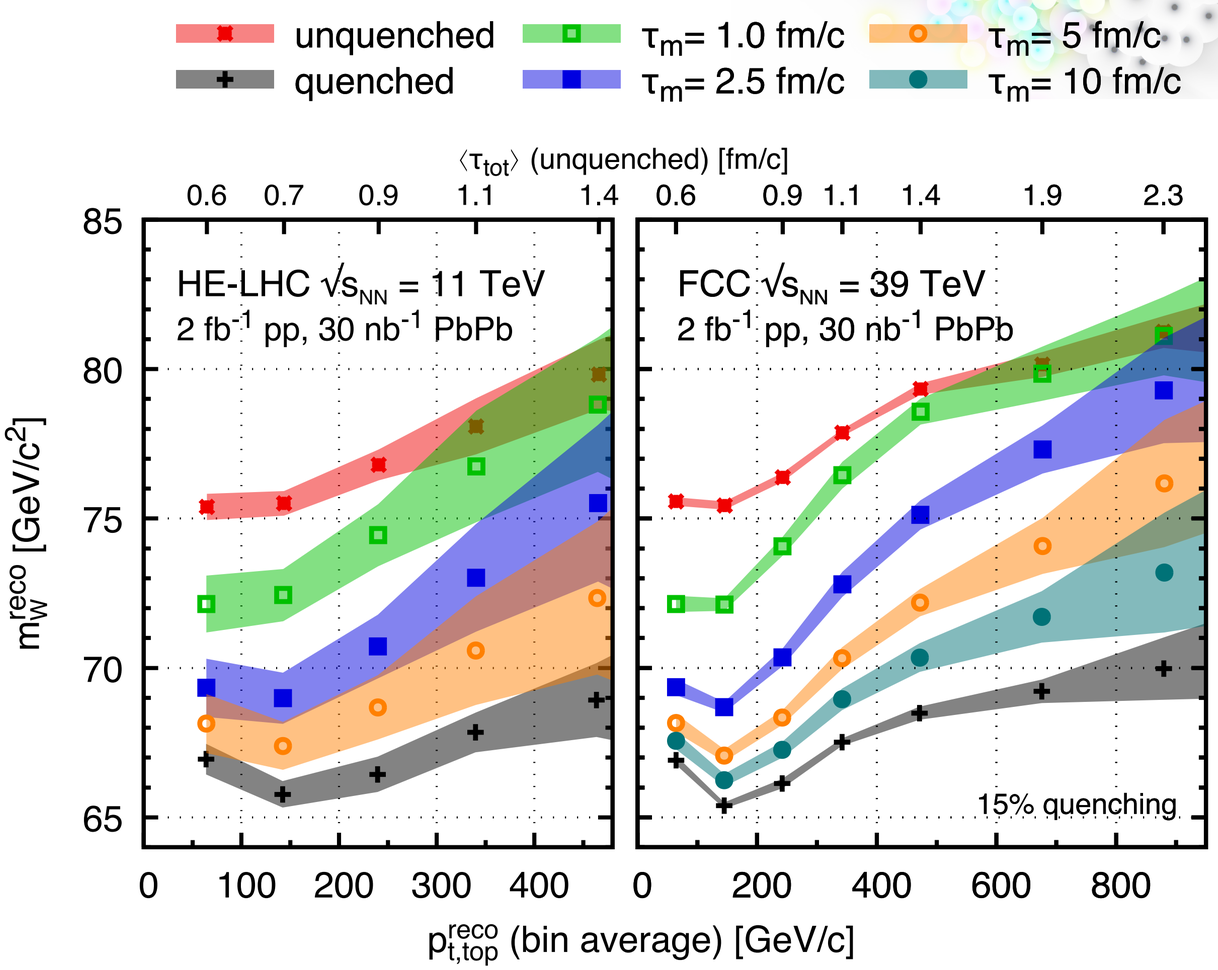
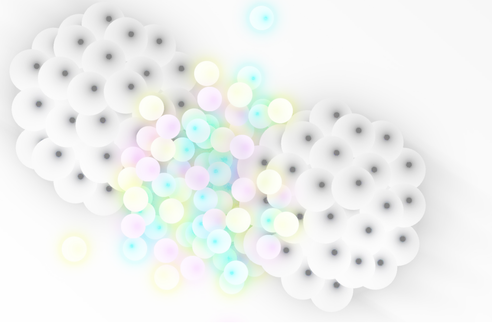


First QGP tomographic analysis

Summary



- Very successful data taking for HIC at LHC was completed (5.02 TeV PbPb, 8.15 TeV pPb).
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    - Rare challenging observables (e.g: photons, di-leptons, jets,…) together with lighter ions, will provide new insight and precise characterisation of the QGP

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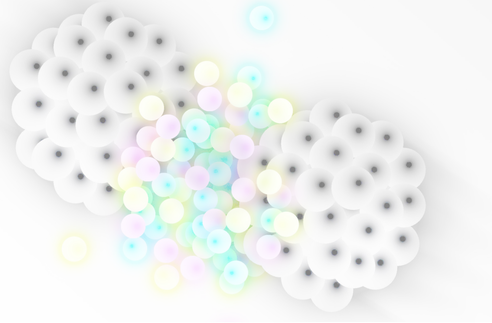

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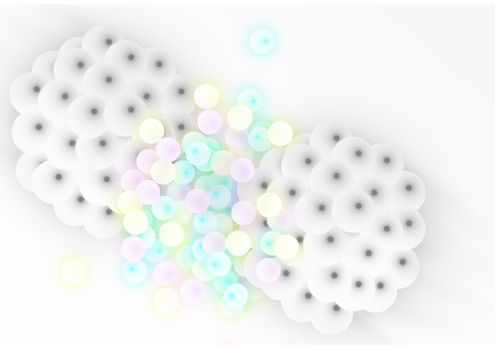

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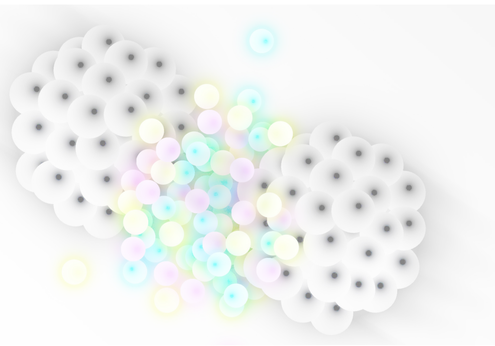

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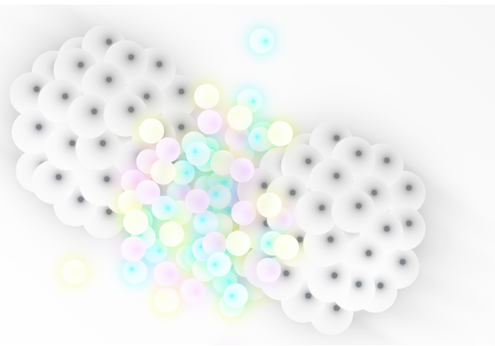
HI collisions open exploration of uncharted QCD phase space (hot and dense) allowing numerous stringent tests to the SM

Thank you!

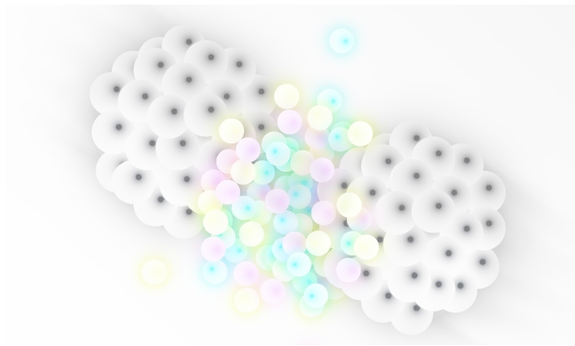
Acknowledgments



Special thanks to:

R. Conceição, G. Milhano, J. Pires

Acknowledgments



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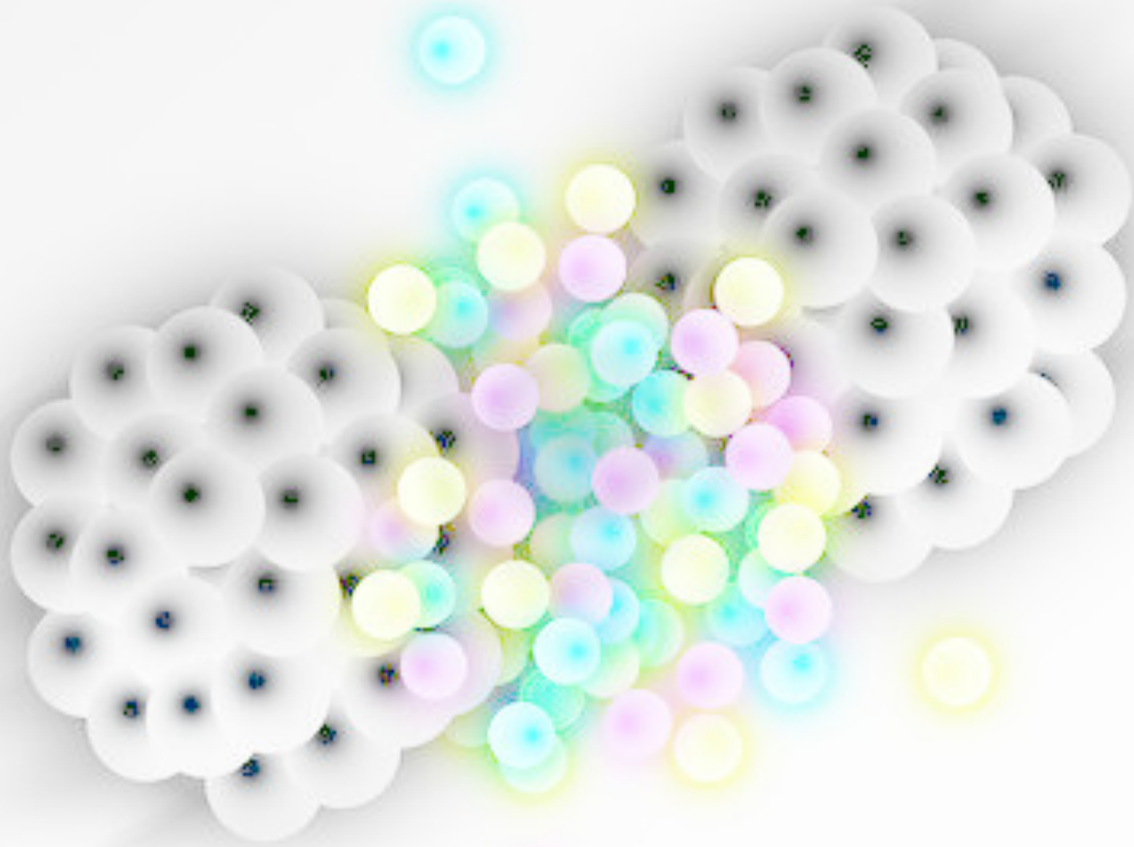
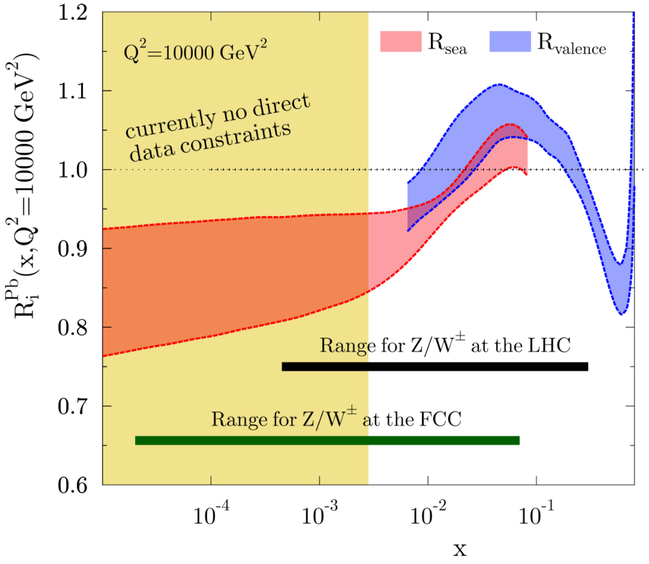


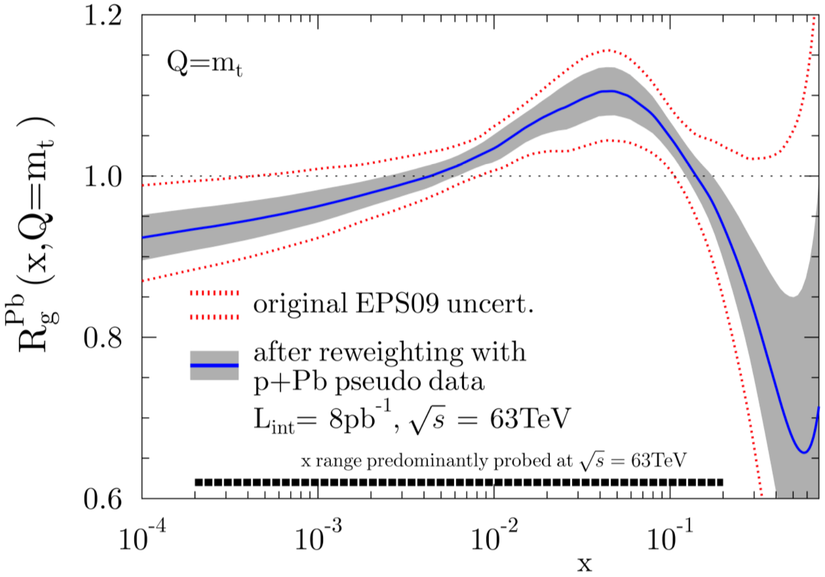
(Nuclear) PDFs

See C. Quintans talk

- Currently, PDFs cannot be computed from first principles

  Need to be extracted from data





New probes provide new **small-x** reach to sea and valence quarks and substantial **constraints** to gluon nPDF

Hints of breaking of linear evolution at HERA but not yet conclusive evidence..

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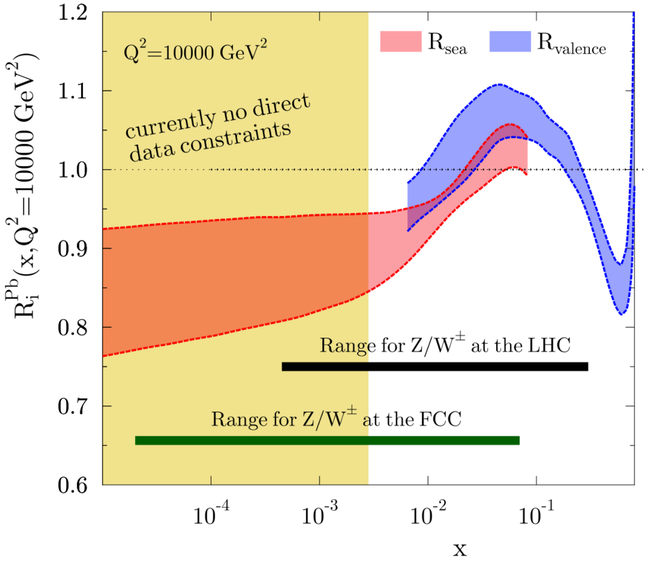

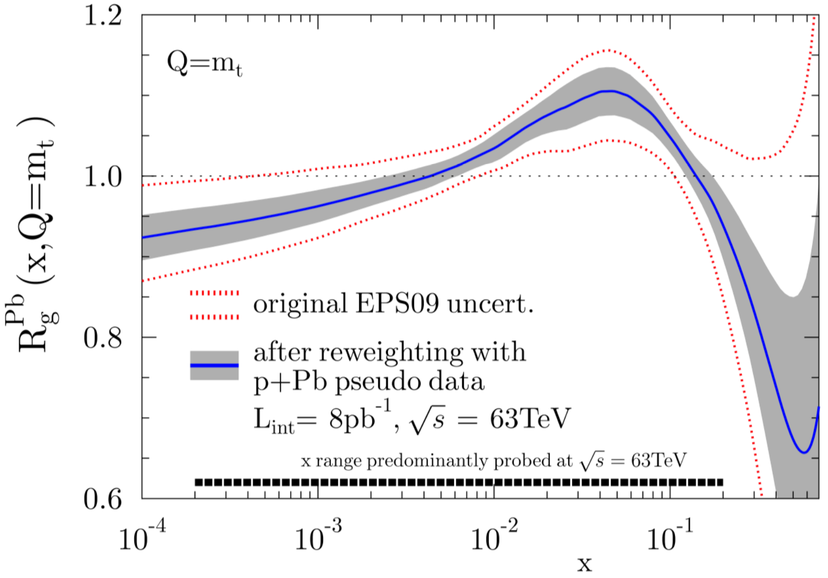

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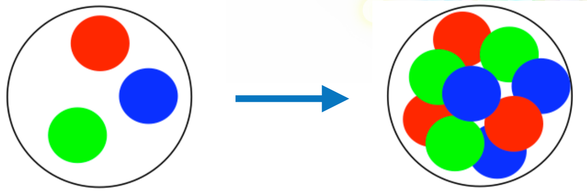

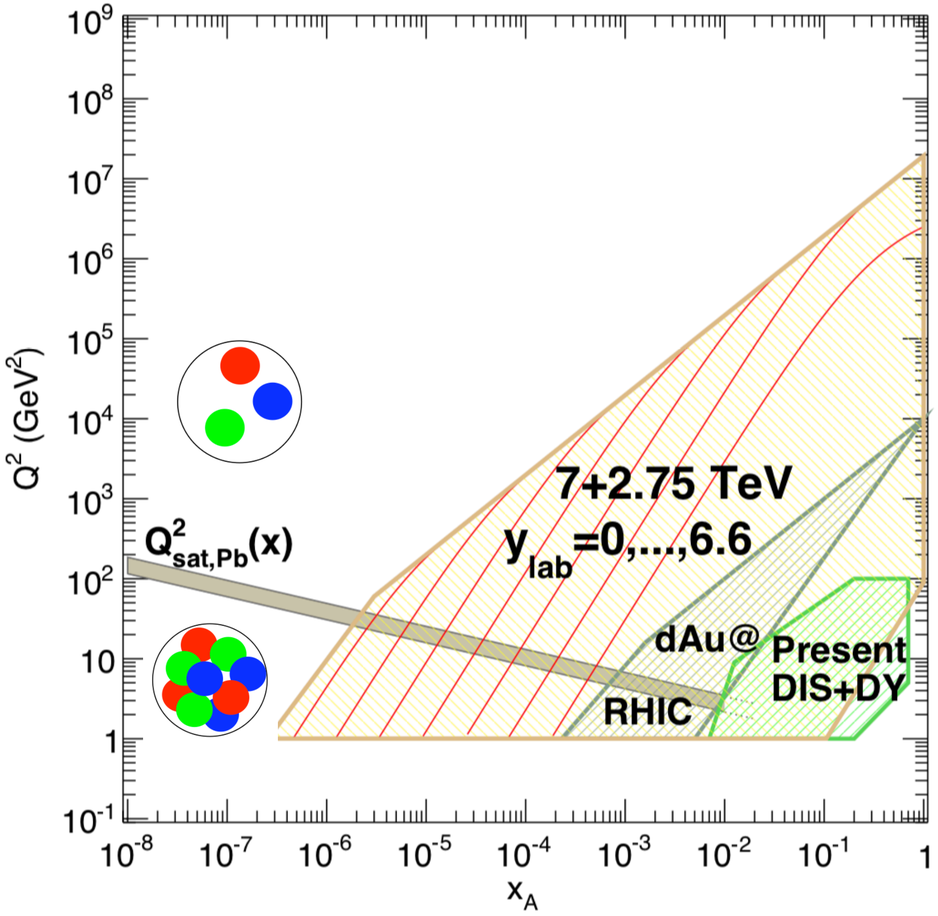

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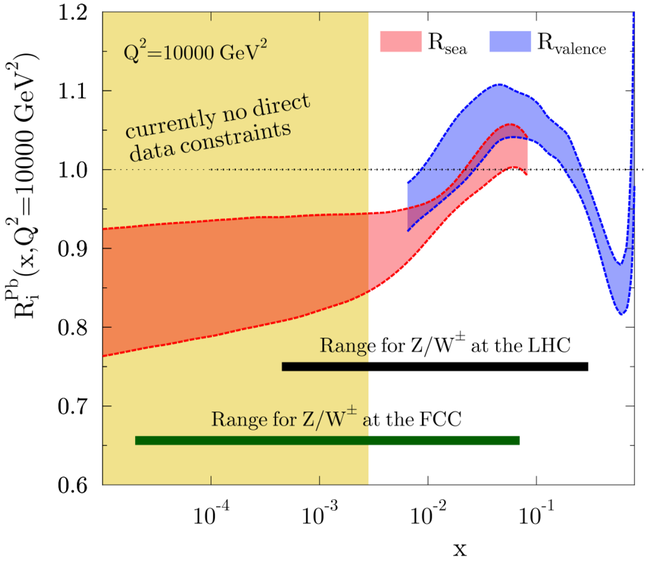

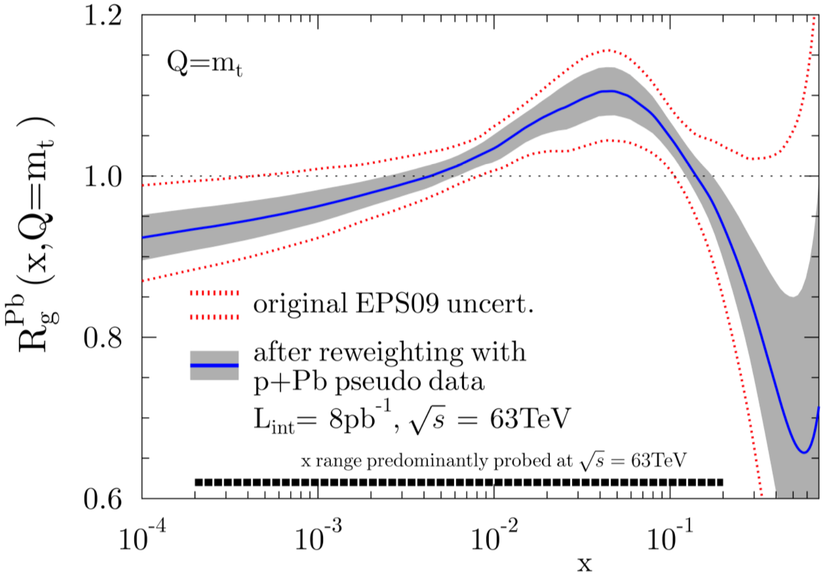

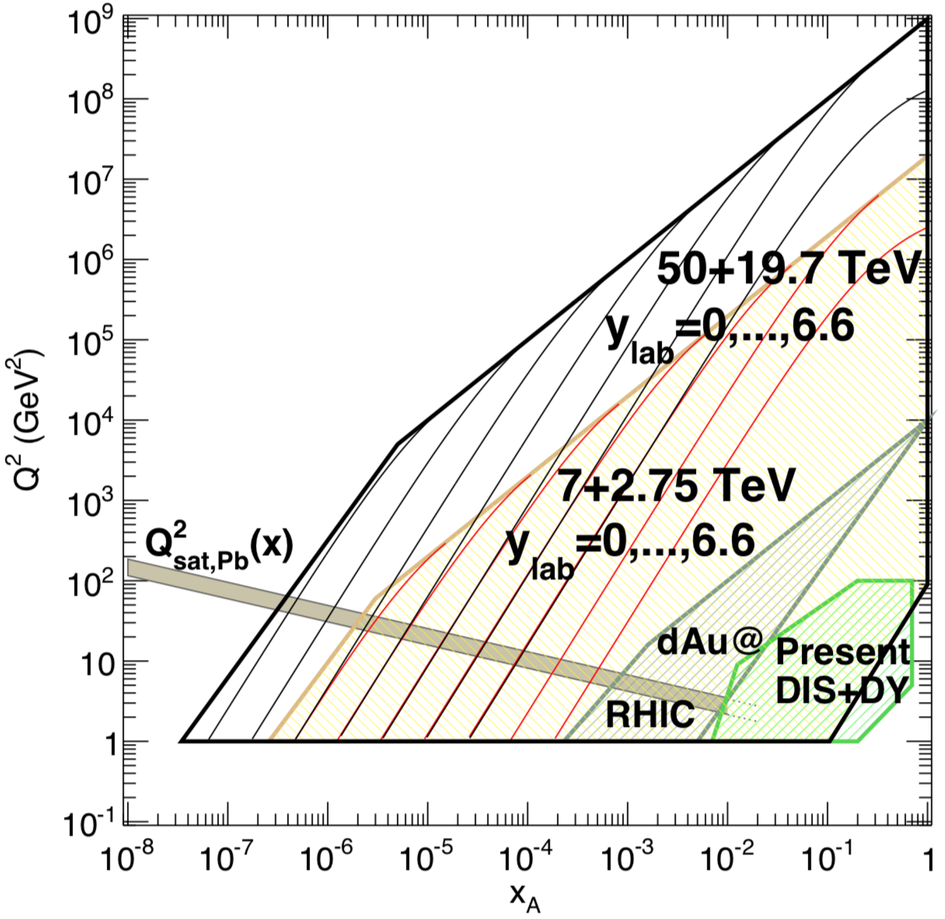

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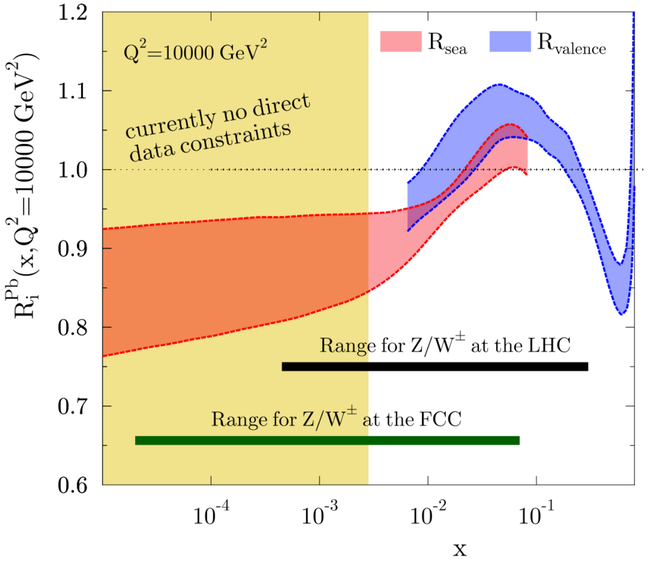

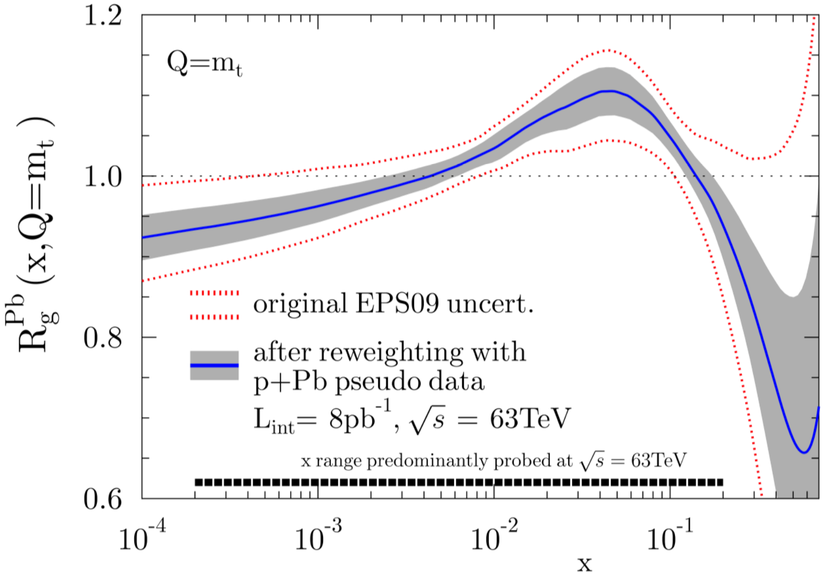

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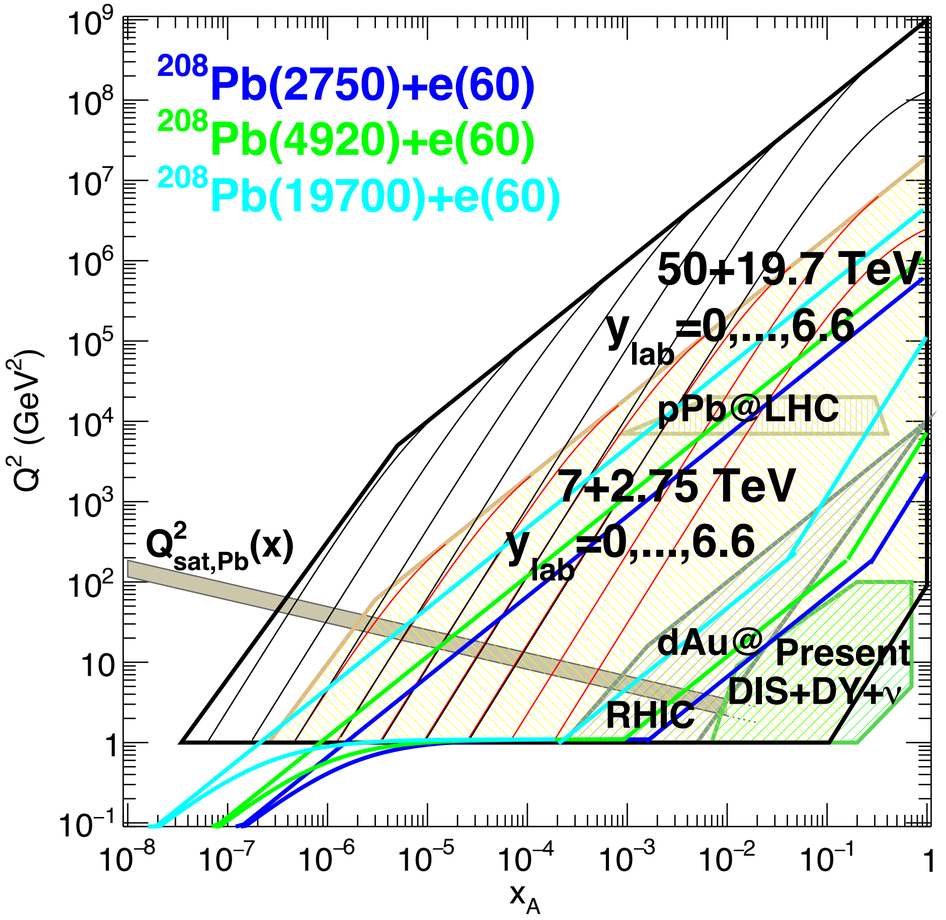
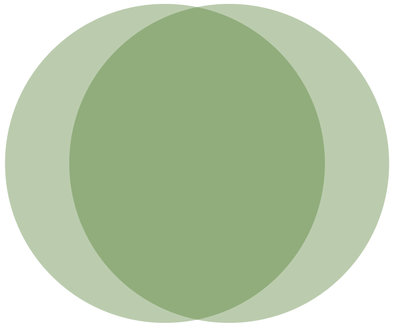
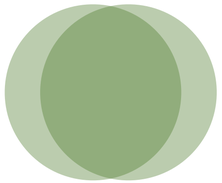


[WG5 on HL/HE-LHC: 1902.01211]

Light Ions



Pb
A = 206



Ar, ??
A = 40, ??

⇧ Volume and Lifetime

⇧ Temperature

⇧ Multiplicity

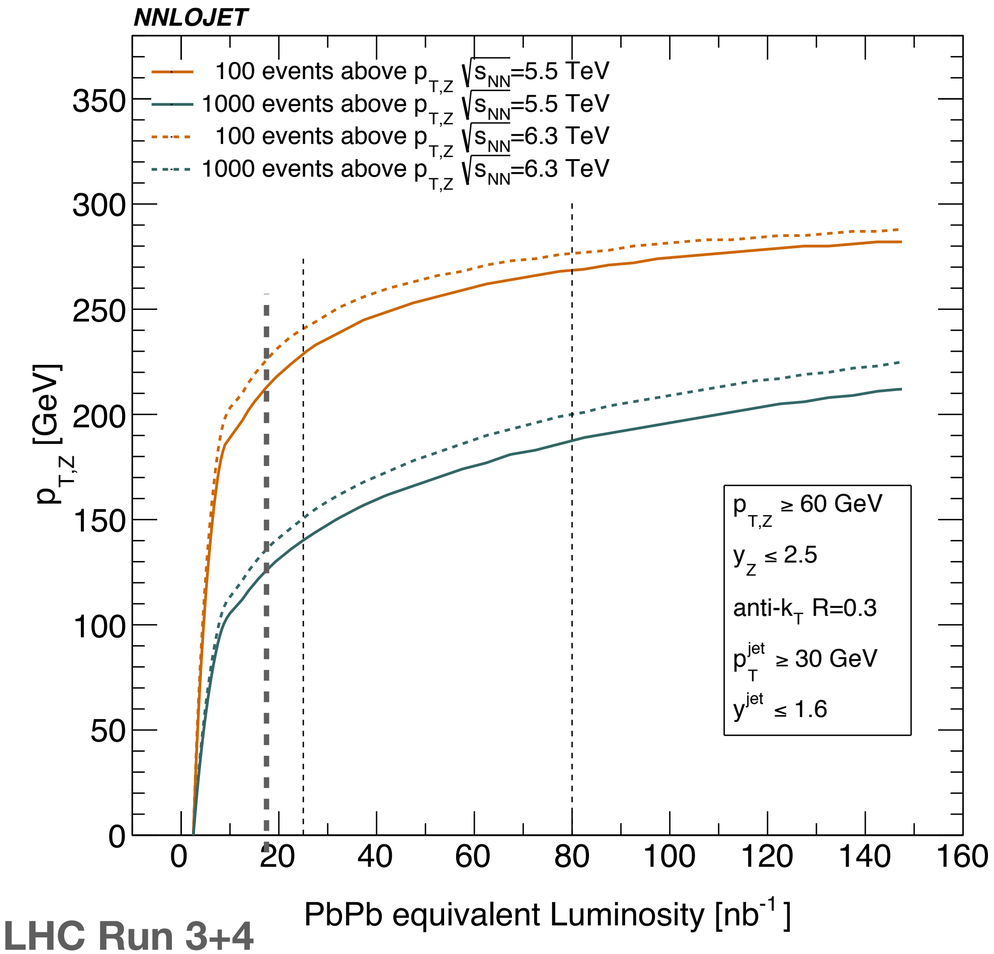
⇩ QGP effects

⇩ Background: **higher precision/ accuracy**

⇧ Luminosity (Production Rate): **unlock rare probes** (Z+jet, ttbar,…)

$$\mathcal{L}_{NN}^{ArAr} = [8; 25] \times \mathcal{L}_{NN}^{PbPb}$$

~ order of magnitude increase in number of hard processes

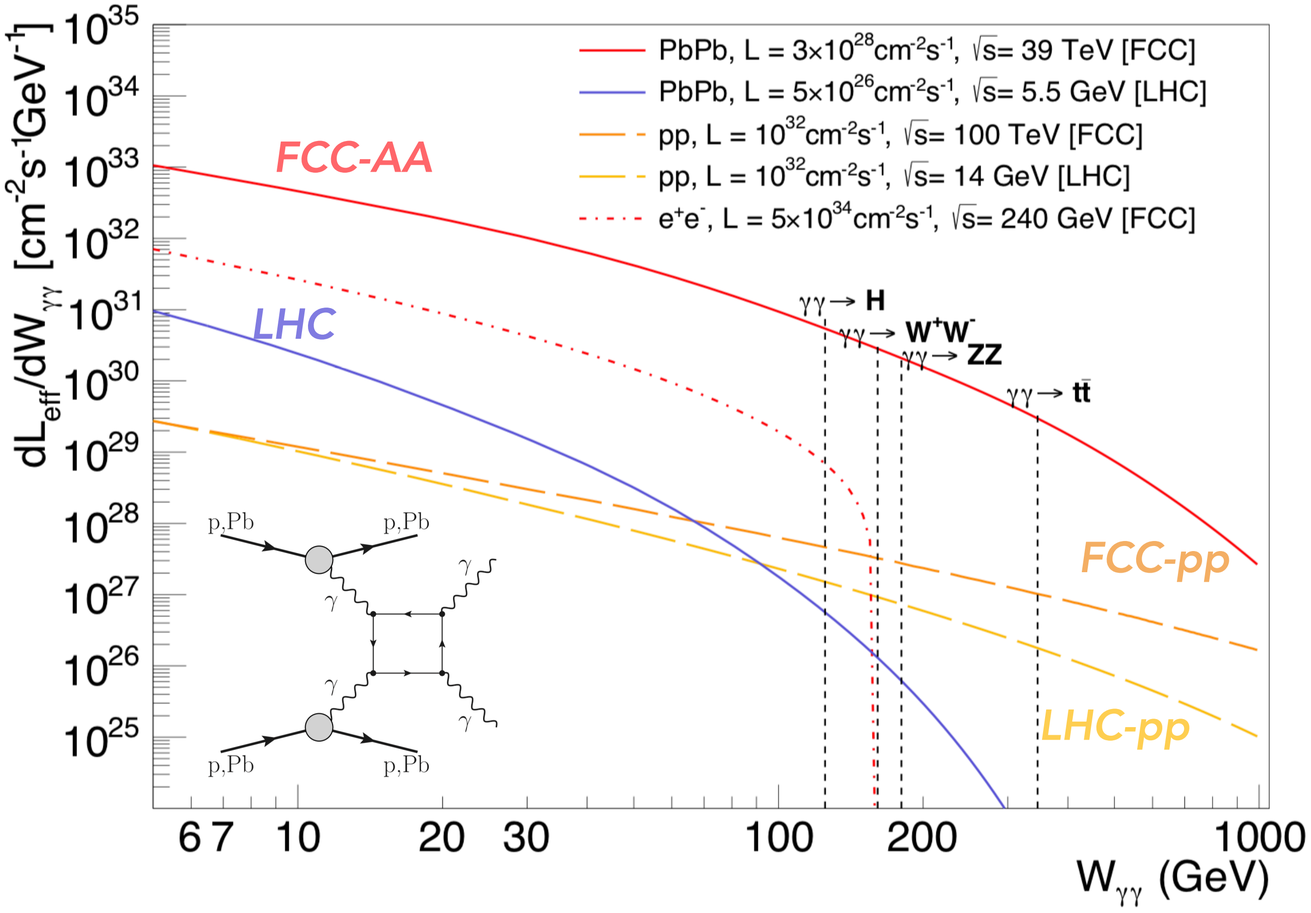


PbPb LHC Run 3+4

d'Enterria et al (17) Knapen et al (17)

γ-γ Collisions

- Effective γγ luminosity: FCC-hh largest γγ luminosity



d'Enterria et al (17) Knapen et al (17)

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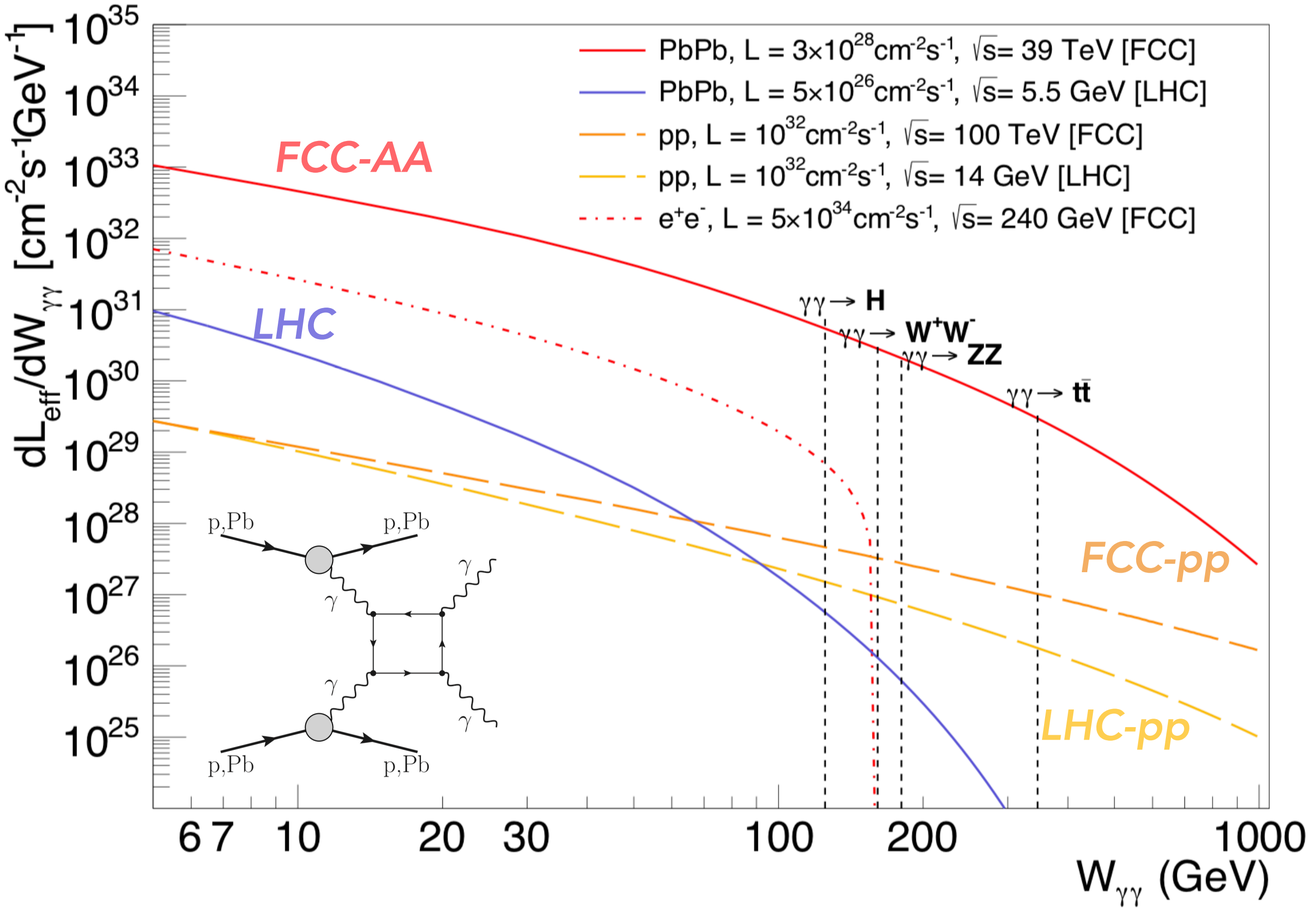

Light-by-light scattering measurement:

- Sensitivity to BSM physics (e.g: new heavy-charged SYSY particles)
- Axion-like particles
- …