LHγC and the EIC to characterize low-x nuclear matter dynamics

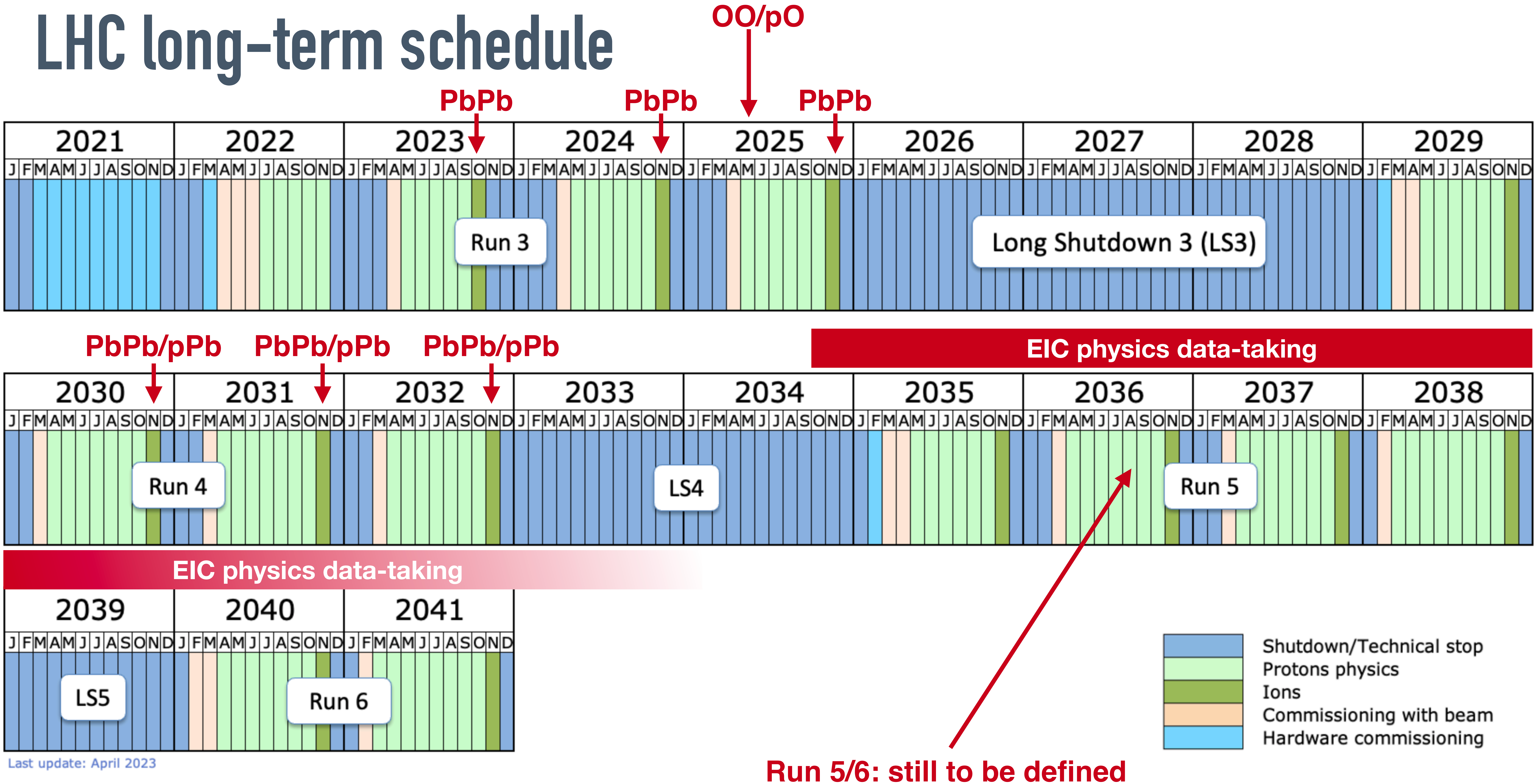
Discussion on LHC Run 5/6 heavy-ion runs

Gian Michele Innocenti, MIT

collecting inputs from many people at this workshops

DIFFRACTION AND GLUON SATURATION AT THE LHC AND THE EIC
10 June 2024 - 14 June 2024

LHC long-term schedule



OO/pO

PbPb

PbPb

PbPb

PbPb/pPb

PbPb/pPb

PbPb/pPb

EIC physics data-taking

EIC physics data-taking

Last update: April 2023

Run 5/6: still to be defined

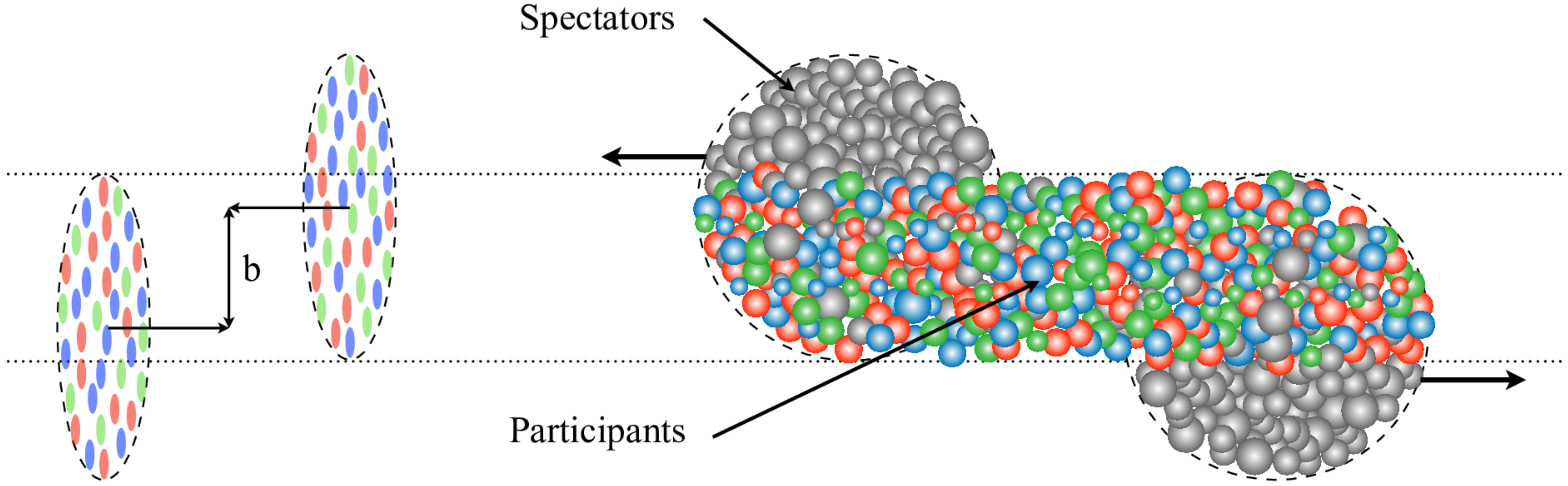
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

Considerations for ion choices for hot QCD studies

ALICE 3 LoI: CERN-LHCC-2022-009

HI Yellow Report, CERN-LPCC-2018-07

Glauber model

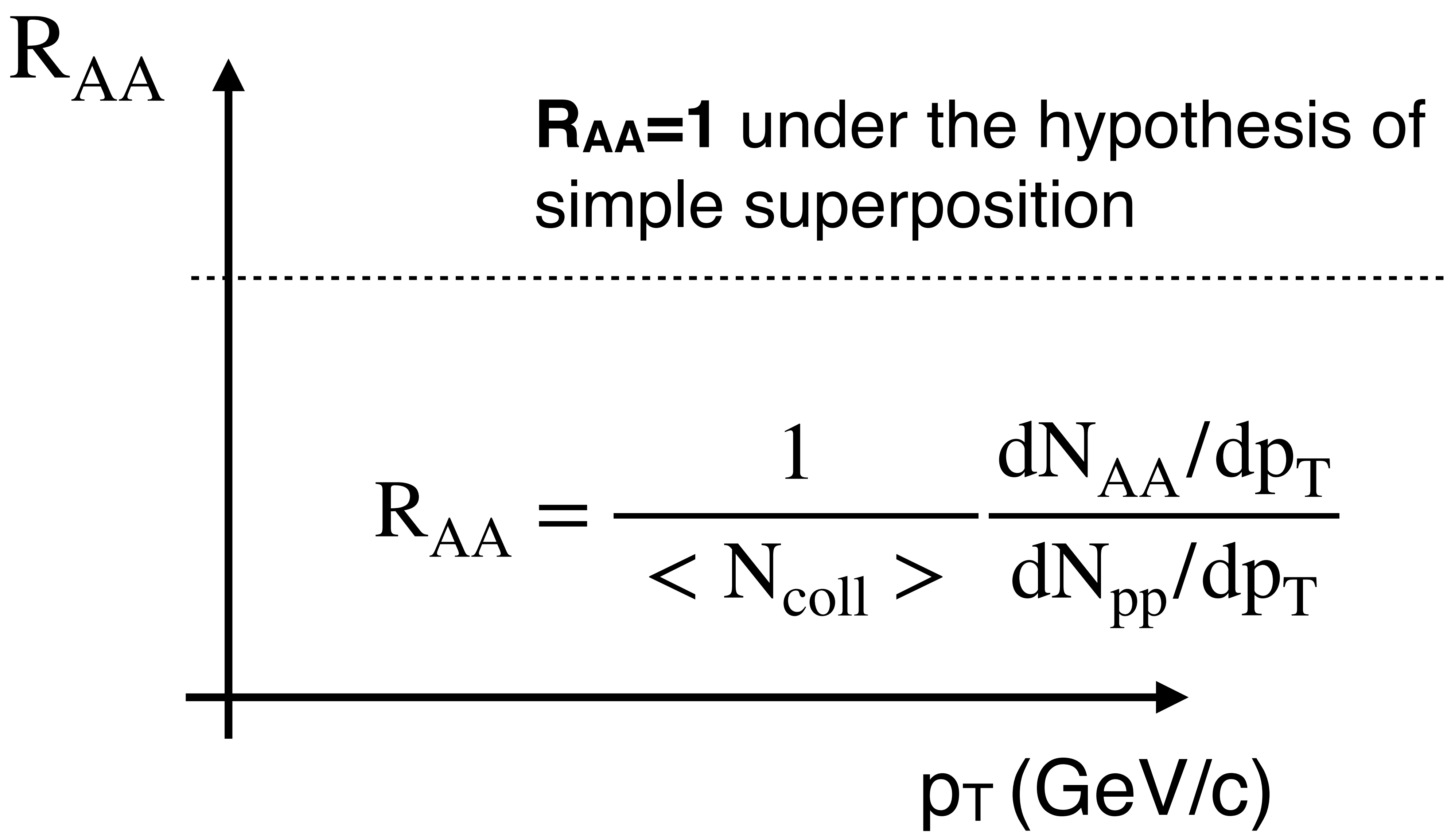


Before collision

After collision

Number of partons participating to the collisions (N_{part})

Centrality	Pb-Pb	Xe-Xe	Kr-Kr	Ar-Ar	O-O
0-5%	1795.4 (153.6)	964.7 (92.6)	511.9 (55.6)	181.0 (26.3)	46.0 (10.3)
5-10%	1402.0 (121.6)	748.7 (75.5)	400.3 (47.3)	144.5 (23.2)	37.5 (9.2)
10-20%	979.8 (151.7)	516.1 (88.4)	277.7 (51.1)	103.3 (22.6)	28.7 (8.6)
20-30%	588.8 (102.0)	303.9 (59.3)	165.2 (35.0)	64.4 (16.1)	19.4 (6.7)
30-40%	336.1 (68.0)	170.3 (38.9)	94.7 (23.3)	39.0 (11.3)	12.8 (5.0)
40-50%	178.4 (43.2)	89.8 (24.1)	51.7 (14.9)	22.9 (7.6)	8.3 (3.7)
50-60%	86.4 (25.1)	44.2 (14.0)	26.6 (8.9)	12.8 (5.0)	5.2 (2.7)
60-70%	37.4 (13.2)	20.1 (7.6)	12.9 (5.2)	6.9 (3.3)	3.3 (1.9)
70-80%	14.1 (6.3)	8.2 (3.9)	5.7 (3.0)	3.5 (2.1)	2.1 (1.3)
80-90%	4.4 (2.7)	3.0 (1.9)	2.4 (1.5)	1.9 (1.1)	1.5 (0.8)
90-100%	1.6 (0.9)	1.4 (0.8)	1.3 (0.7)	1.3 (0.6)	1.2 (0.5)



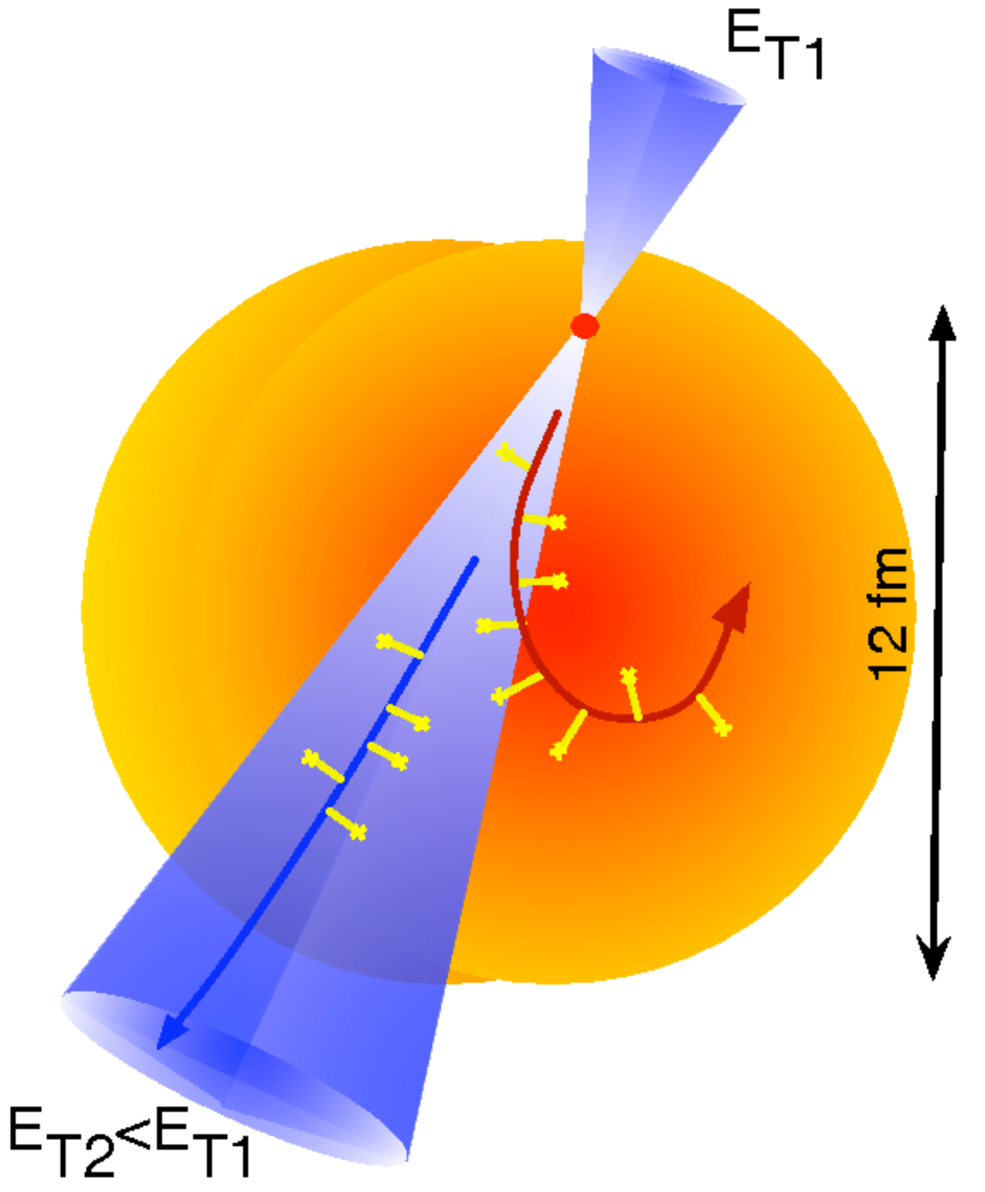
R_{AA}=1 under the hypothesis of simple superposition

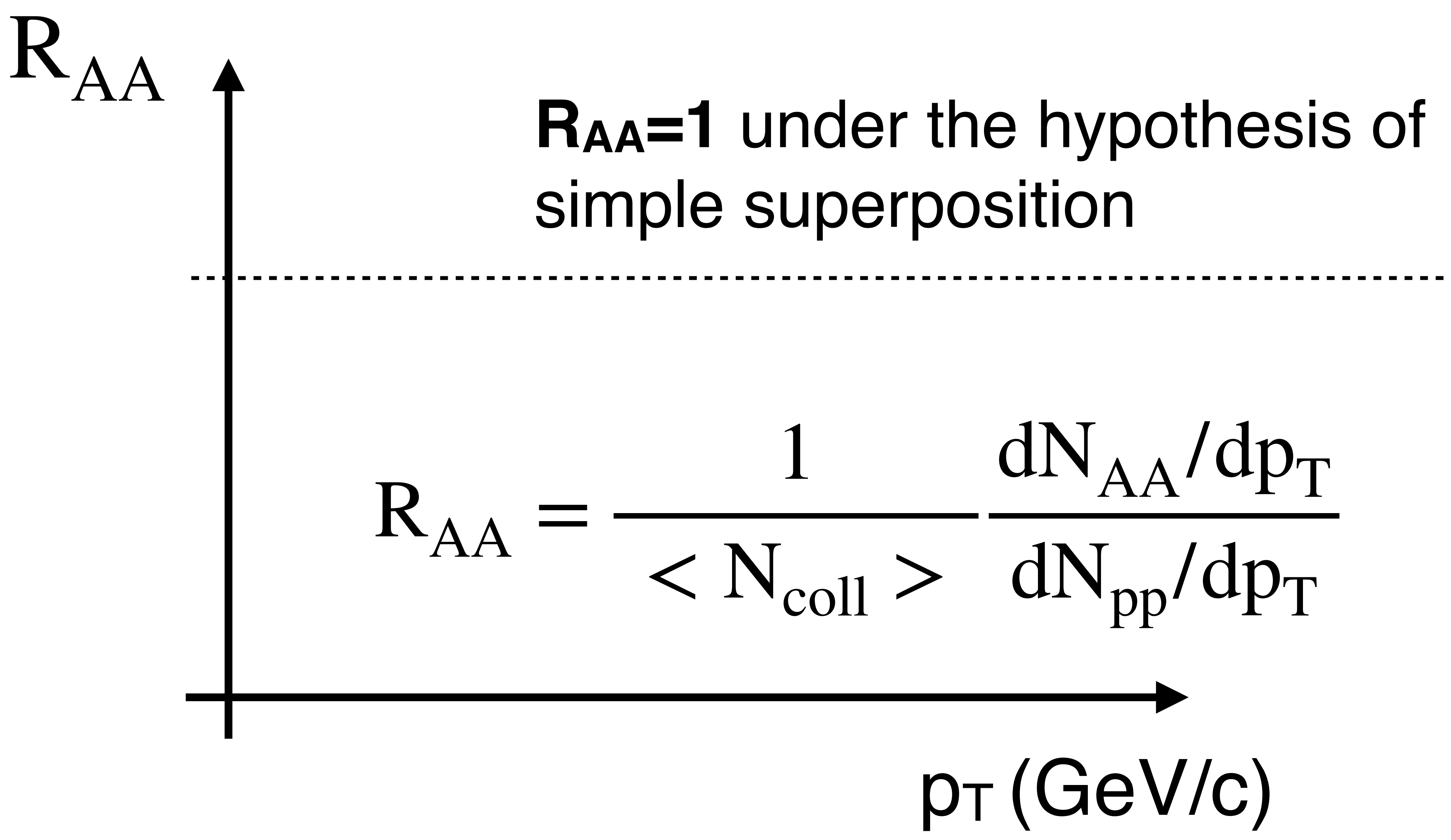
$$R_{AA} = \frac{1}{< N_{coll} >} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Number of binary NN collisions (N_{coll})

Centrality	Pb-Pb	Xe-Xe	Kr-Kr	Ar-Ar	O-O
0-5%	383.4 (17.6)	236.7 (11.0)	152.2 (7.9)	70.9 (4.6)	26.9 (2.6)
5-10%	332.0 (19.7)	207.3 (13.2)	134.2 (9.6)	63.6 (5.7)	24.3 (3.2)
10-20%	262.5 (27.5)	165.0 (18.0)	107.7 (12.3)	52.1 (6.7)	20.7 (3.6)
20-30%	187.6 (21.8)	118.2 (14.7)	77.7 (10.2)	38.7 (5.8)	16.0 (3.4)
30-40%	129.9 (17.2)	81.7 (11.6)	54.2 (8.2)	27.8 (4.9)	12.0 (3.0)
40-50%	85.7 (13.2)	53.7 (9.0)	36.1 (6.5)	19.2 (4.1)	8.8 (2.7)
50-60%	52.9 (9.8)	33.1 (6.7)	22.6 (5.0)	12.6 (3.4)	6.2 (2.3)
60-70%	29.5 (7.0)	18.6 (4.9)	13.1 (3.8)	7.8 (2.7)	4.3 (1.8)
70-80%	14.3 (4.6)	9.3 (3.4)	6.9 (2.7)	4.6 (2.0)	3.1 (1.3)
80-90%	5.7 (2.7)	4.2 (2.0)	3.5 (1.6)	2.9 (1.2)	2.5 (0.8)
90-100%	2.6 (1.0)	2.4 (0.8)	2.4 (0.7)	2.3 (0.6)	2.2 (0.5)

Choosing the right ion for hot-QCD studies: jet quenching





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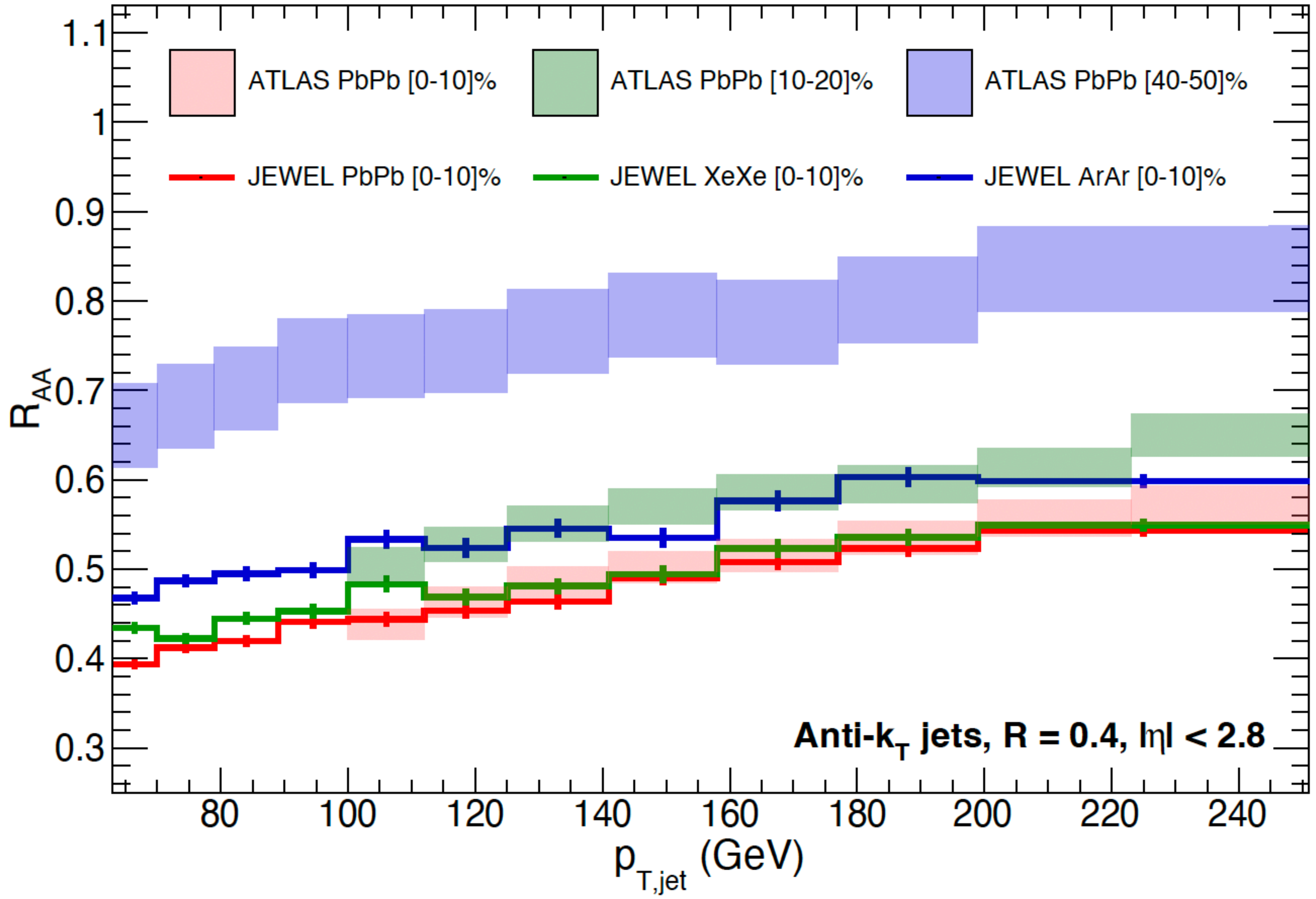


Main need is to have a QCD medium that is large and hot enough, with a long life-time to have strong sensitivity to interactions with the partonic constituents

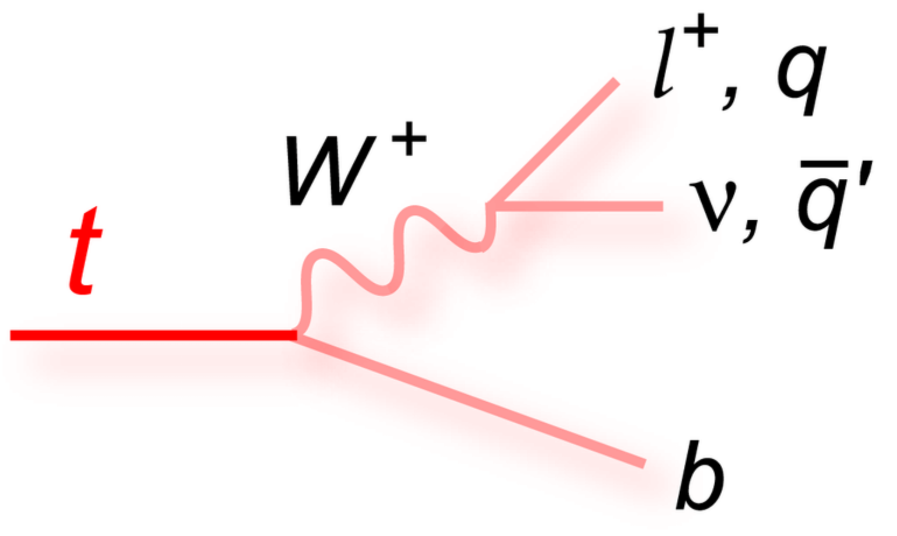
Casalderrey-Solana, J. et al - CERN-PH-TH-2011-168
HI Yellow Report, CERN-LPCC-2018-07

Yoctosecond structure of the QGP with top quarks

→ study differentially the space-time evolution of the medium created in heavy ion collisions

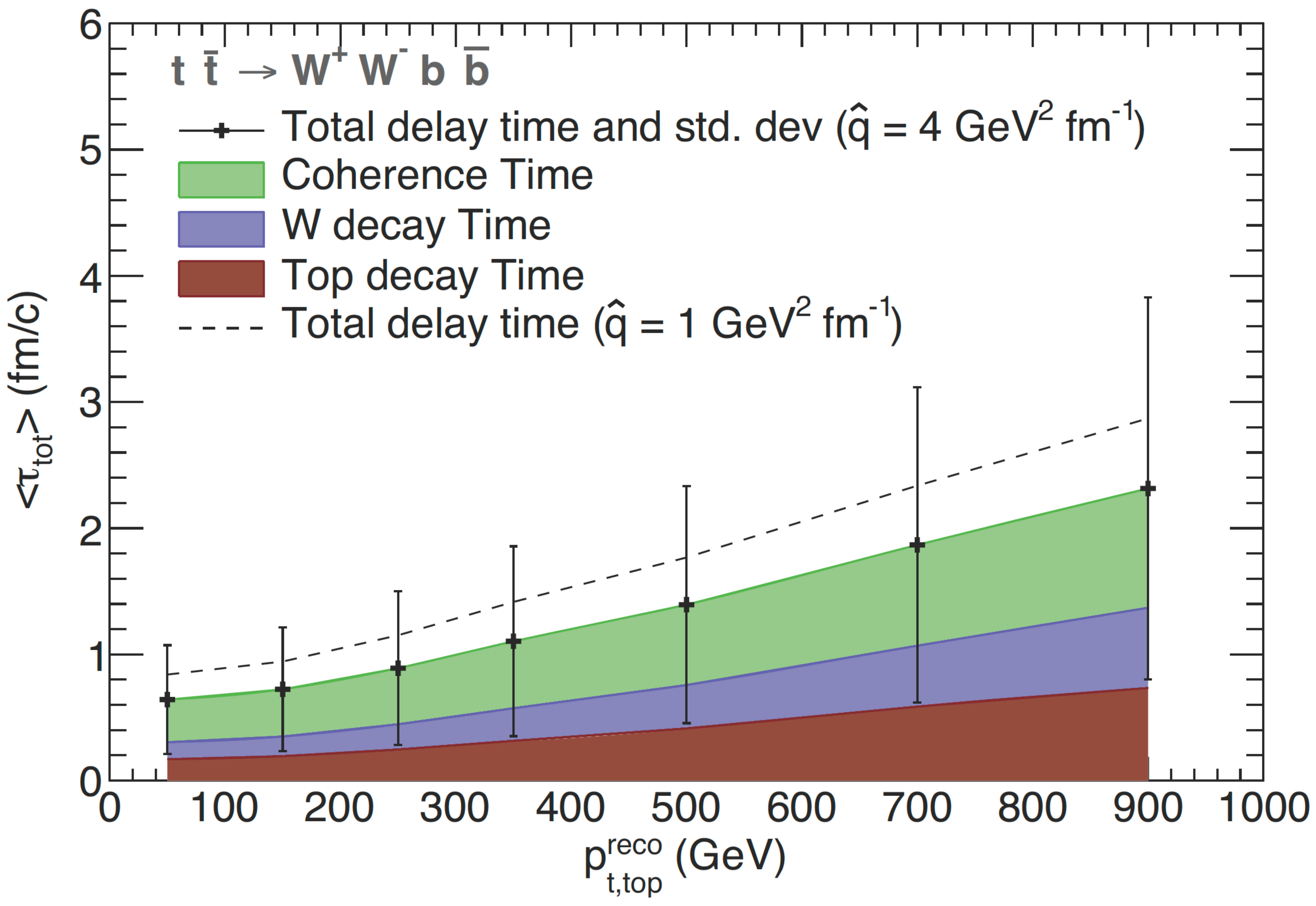
L. Apolinário, J.G. Milhano, G. P. Salam, C. A. Salgado, Phys. Rev. Lett. 120, 232301 (2018)

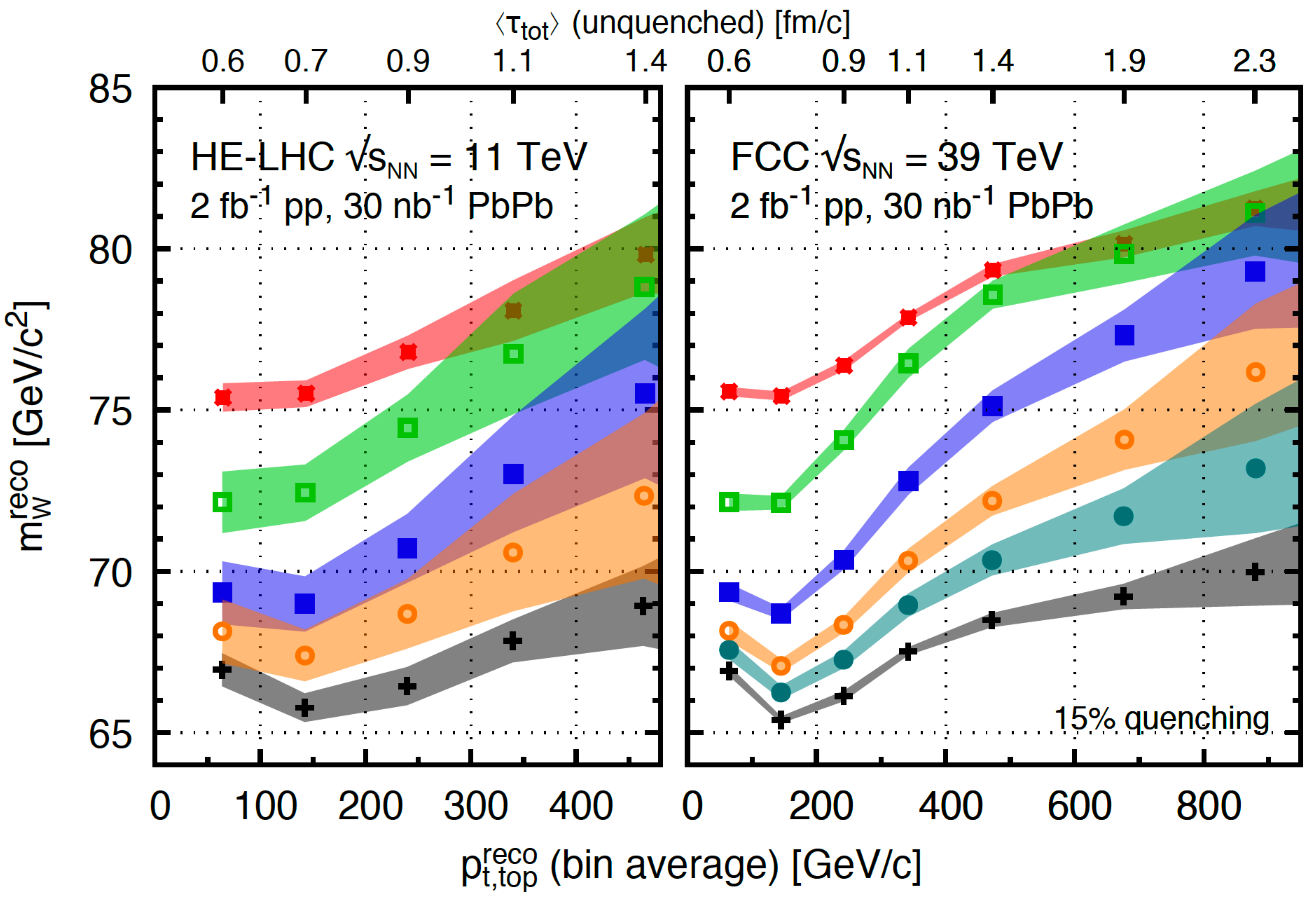
$$\langle \tau_{\rm tot} \rangle = \gamma_{t,{\rm top}} \tau_{\rm top} + \gamma_{t,W} \tau_W + \tau_d$$



$$\tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}} \right)^{1/3}$$

decoherence time of the $q\bar{q}$ singlet

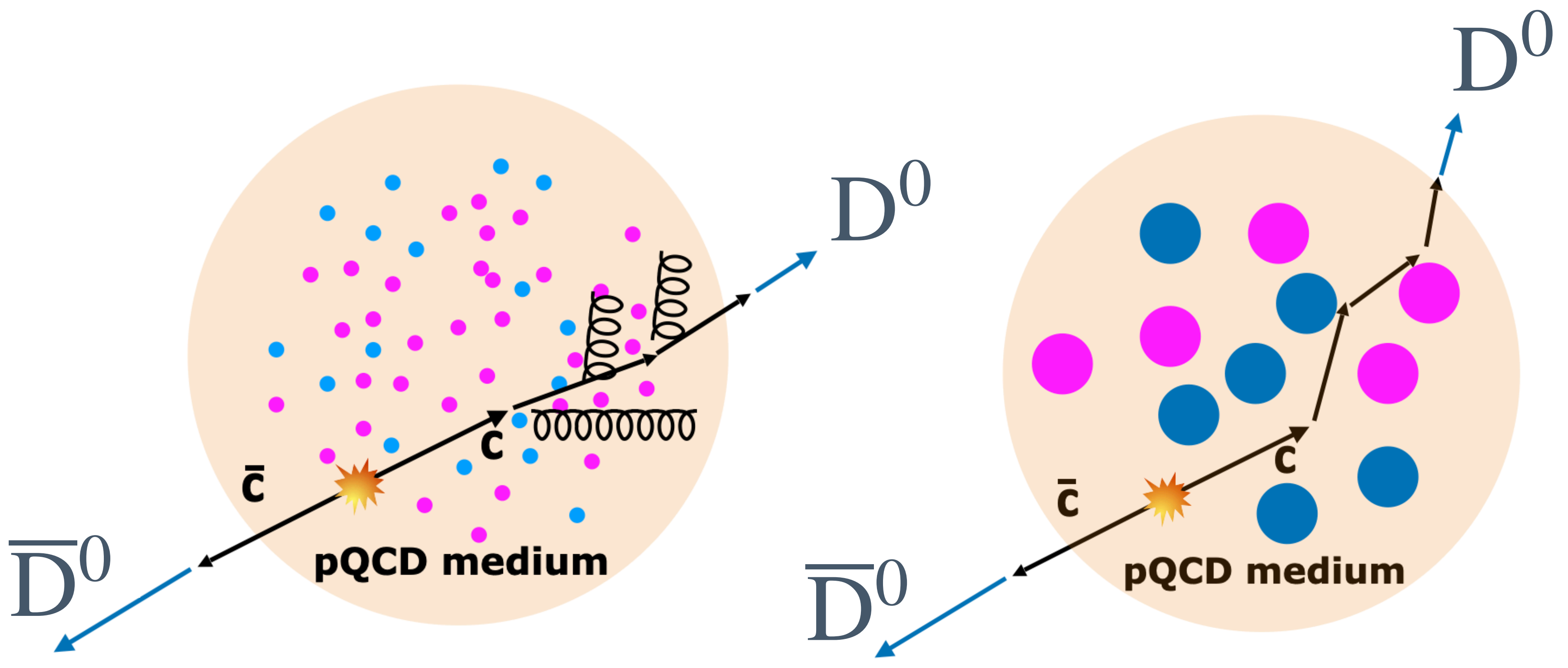




→ effect of quenching observed via the shift in the invariant mass of the m_{jj} of the diet decays

Heavy-flavor correlations

“Rutherford-like” experiment with $D^0\overline{D}^0$ correlations



→ partonic “structure” of the hot medium

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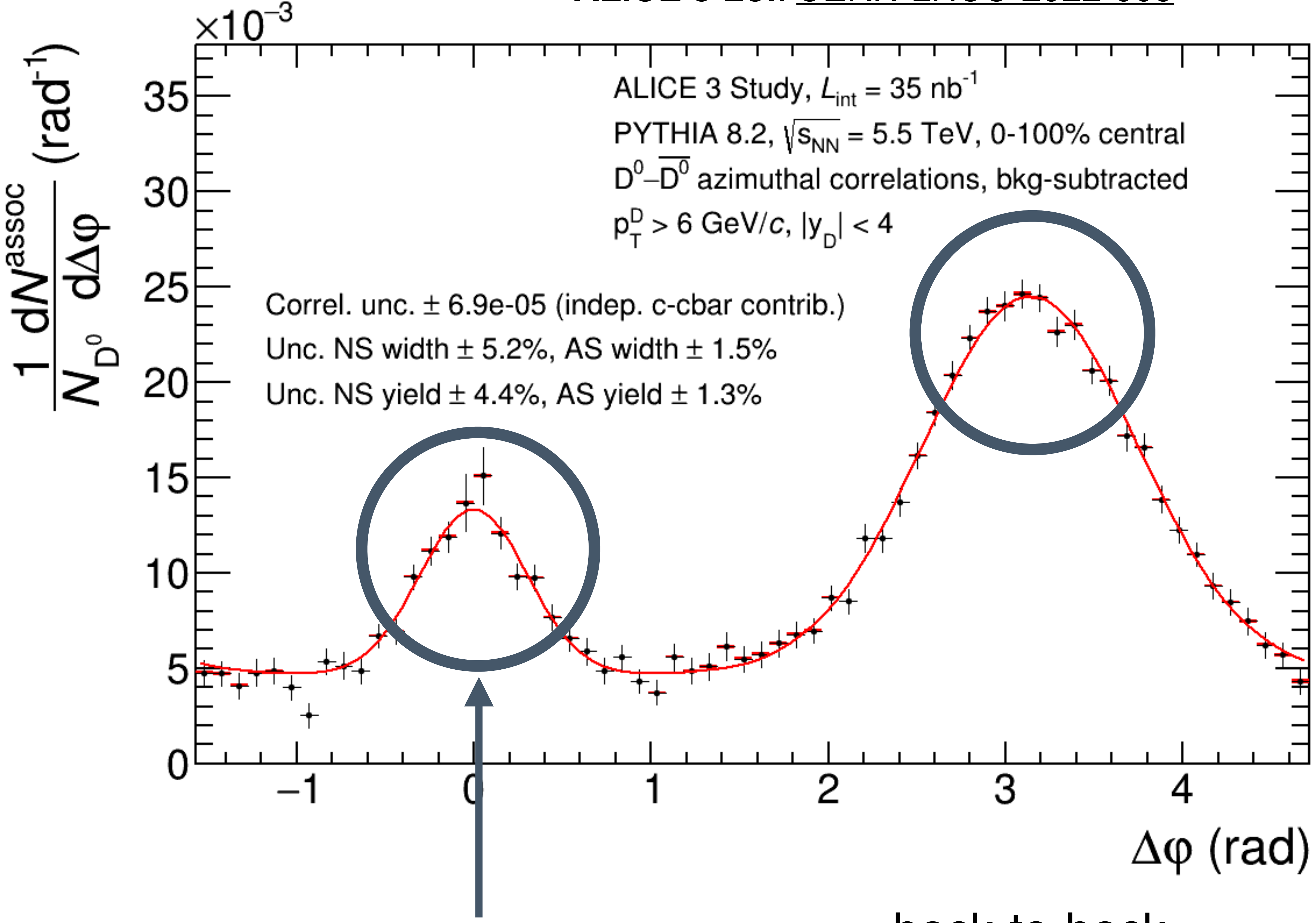
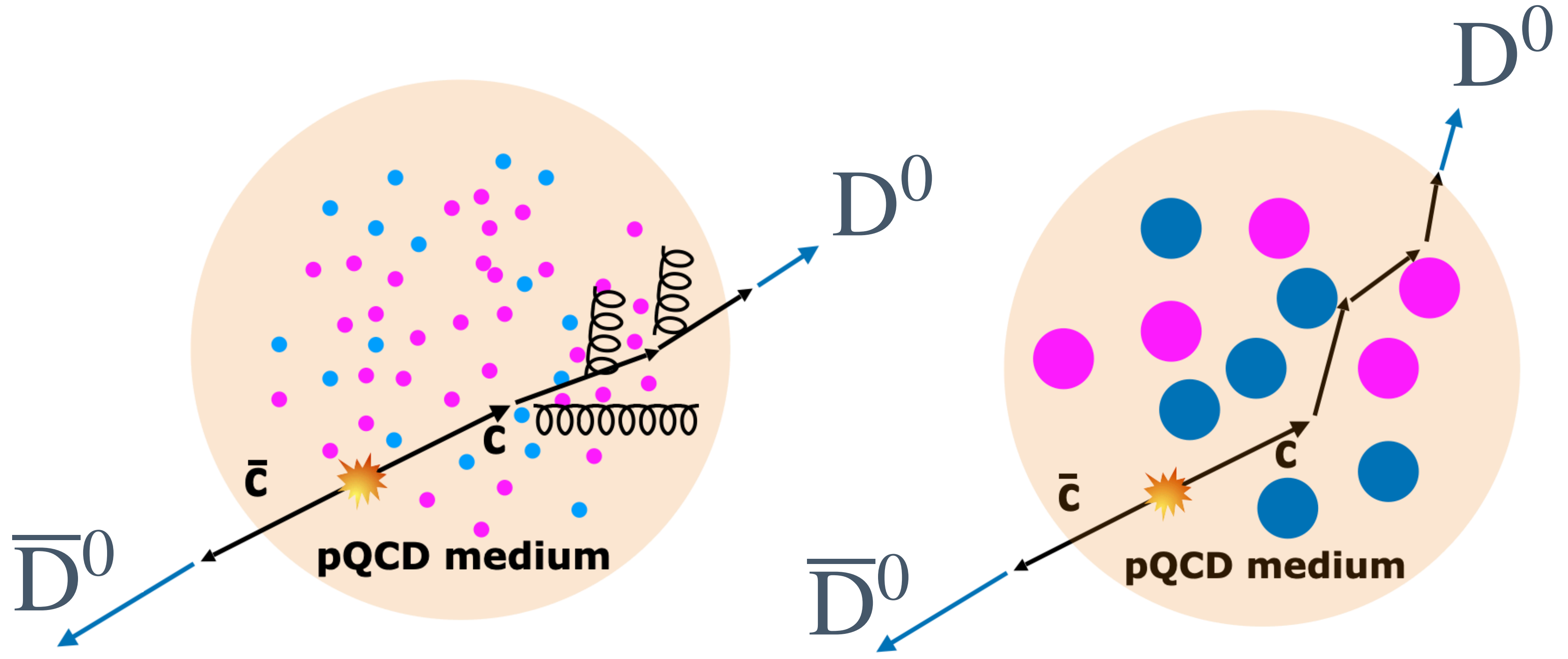


“collinear” $g\rightarrow c\bar{c}$

back-to-back
$c\bar{c}$ pairs

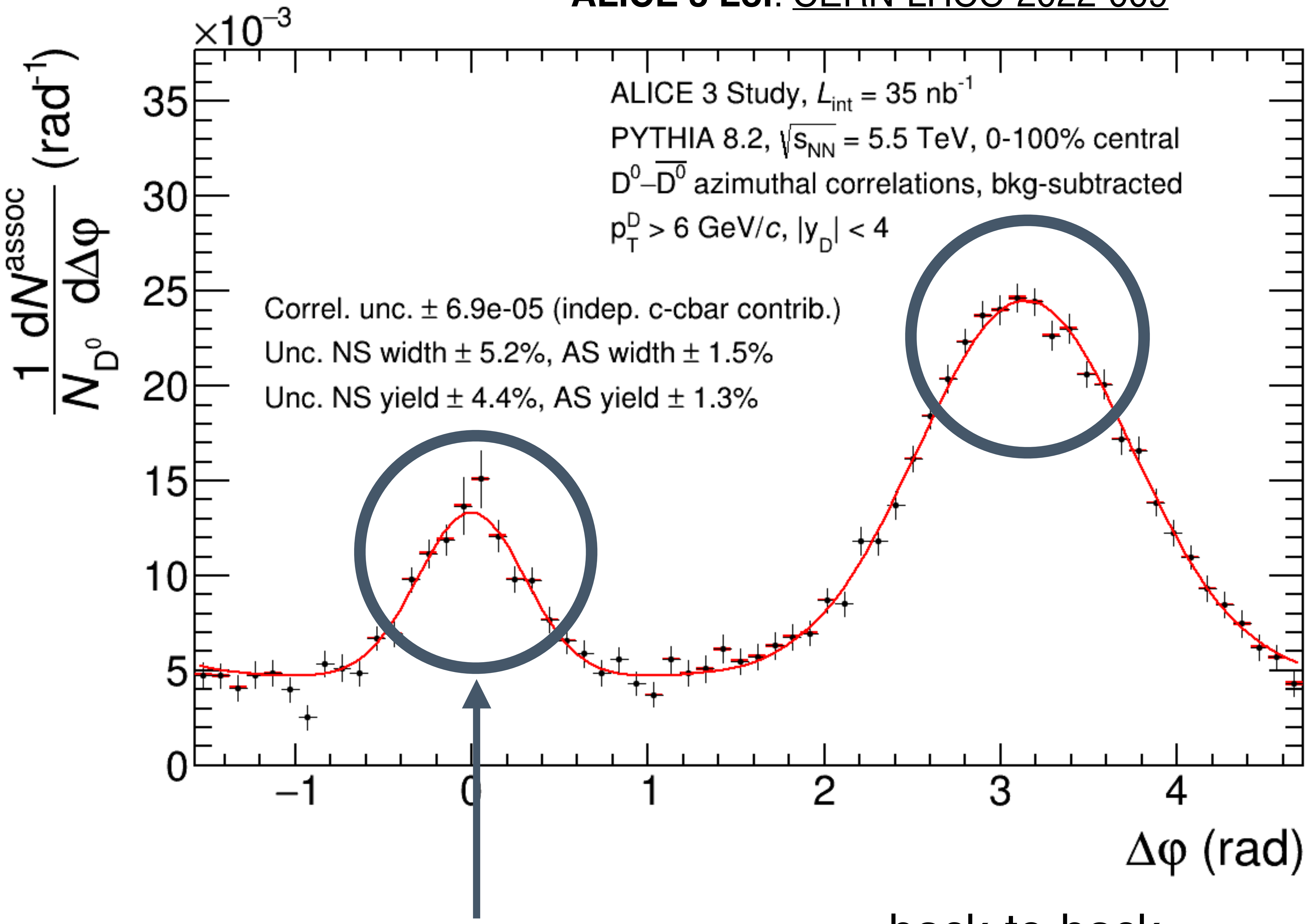
Heavy-flavor correlations

“Rutherford-like” experiment with $D^0\overline{D}^0$ correlations



→ partonic “structure” of the hot medium

ALICE 3 LoI: CERN-LHCC-2022-009



“collinear” g→c$\bar{c}$

back-to-back
c$\bar{c}$ pairs

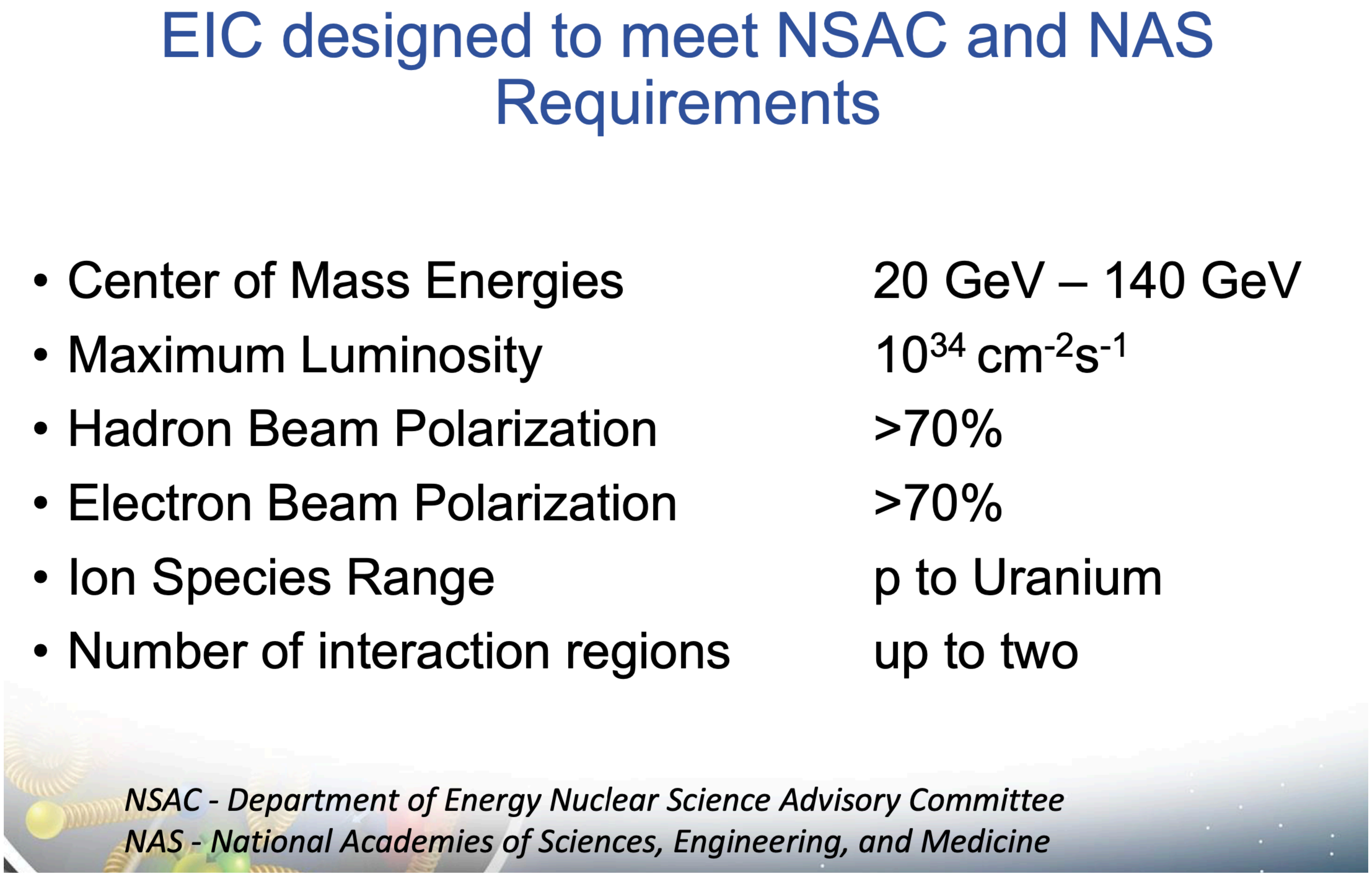
Based on these requirements, **there will be a preference for having a single “best” ion, for which one tries to collect very high statistics,** instead of splitting it in multiple data-taking periods with different ions

EIC collider: some numbers

ALICE 3 LoI: CERN-LHCC-2022-009

EIC collider parameters

Andrei Seryi, EIC Workshop - 7 October 2020



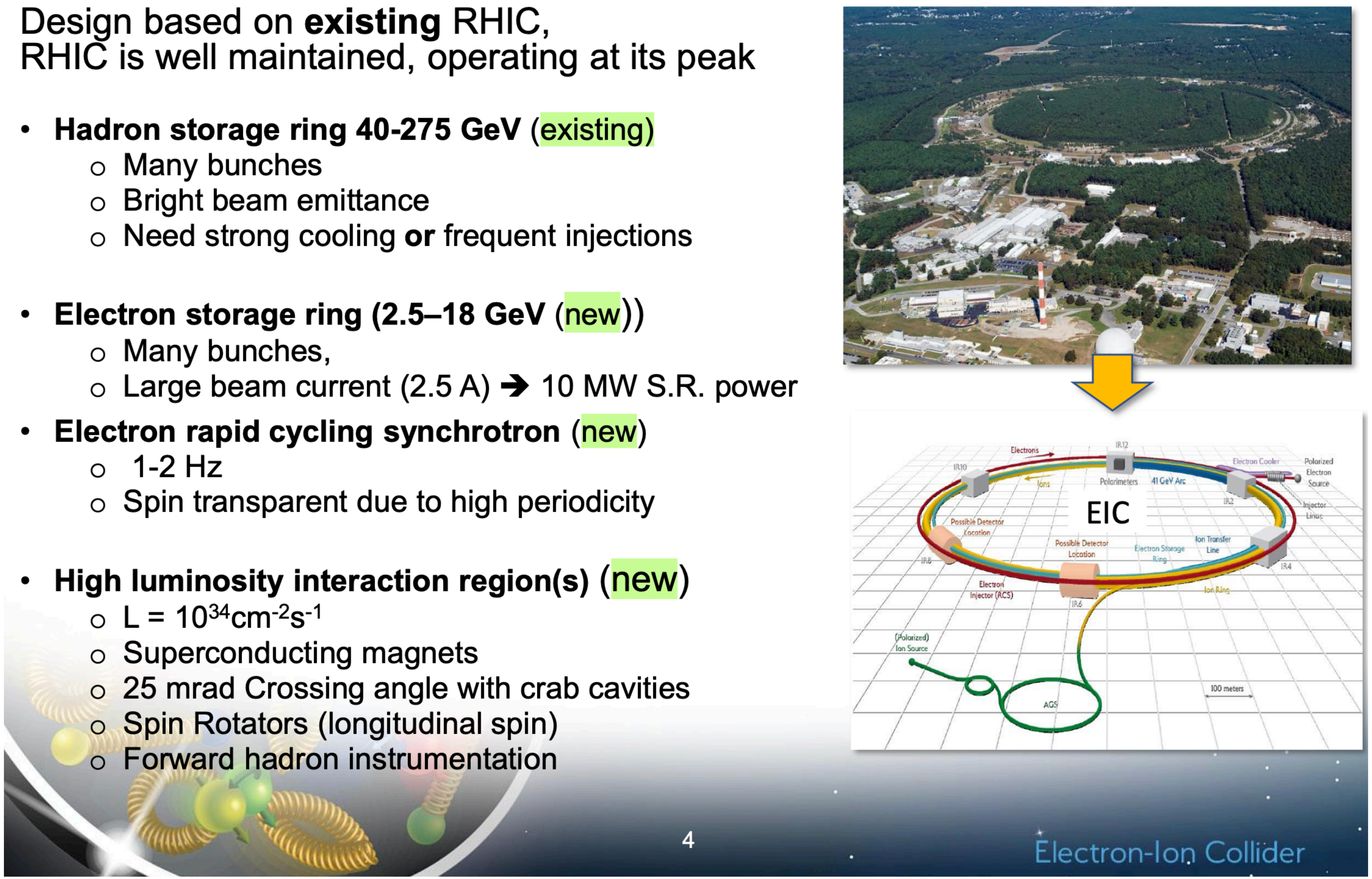
EIC designed to meet NSAC and NAS Requirements

• Center of Mass Energies	20 GeV – 140 GeV
• Maximum Luminosity	10^{34} cm^{-2}s^{-1}
• Hadron Beam Polarization	>70%
• Electron Beam Polarization	>70%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

NSAC - Department of Energy Nuclear Science Advisory Committee
NAS - National Academies of Sciences, Engineering, and Medicine

EIC collider parameters

Andrei Seryi, EIC Workshop - 7 October 2020

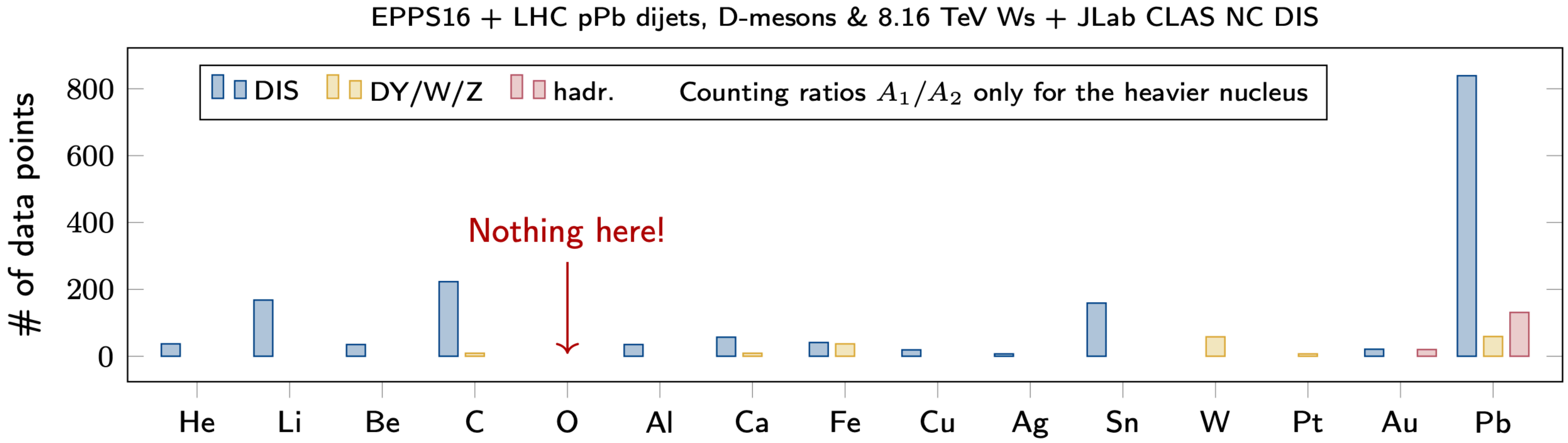


Design based on **existing** RHIC,
RHIC is well maintained, operating at its peak

- **Hadron storage ring 40-275 GeV** (existing)
  - Many bunches
  - Bright beam emittance
  - Need strong cooling **or** frequent injections
- **Electron storage ring (2.5–18 GeV** (new))
  - Many bunches,
  - Large beam current (2.5 A) ➔ 10 MW S.R. power
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
  - L = $10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation

Some inputs from the OO/pO oxygen run workshop (2021)

Data availability w.r.t. A



$\sim 50\%$ of the data points are for Pb!

- ☺ Good coverage of DIS measurements for different A
- 😐 DY data more scarce, but OK A coverage
- ☹ Hadronic observables available only for heavy nuclei!

Light-ion runs at LHC could:

- Complement other light-nuclei DY data with W and Z production (strangeness!)
- Give first direct constraints (e.g. dijets, D-mesons) on light-nuclei gluon distributions!

Petja Paakkinen, Opportunities of OO and pO collisions at the LHC (2021), link

Dijet $R_{\mathrm{pO}}^{\mathrm{norm.}}$ in pO at 9.9 TeV

Excellent cancellation of free-proton PDFs

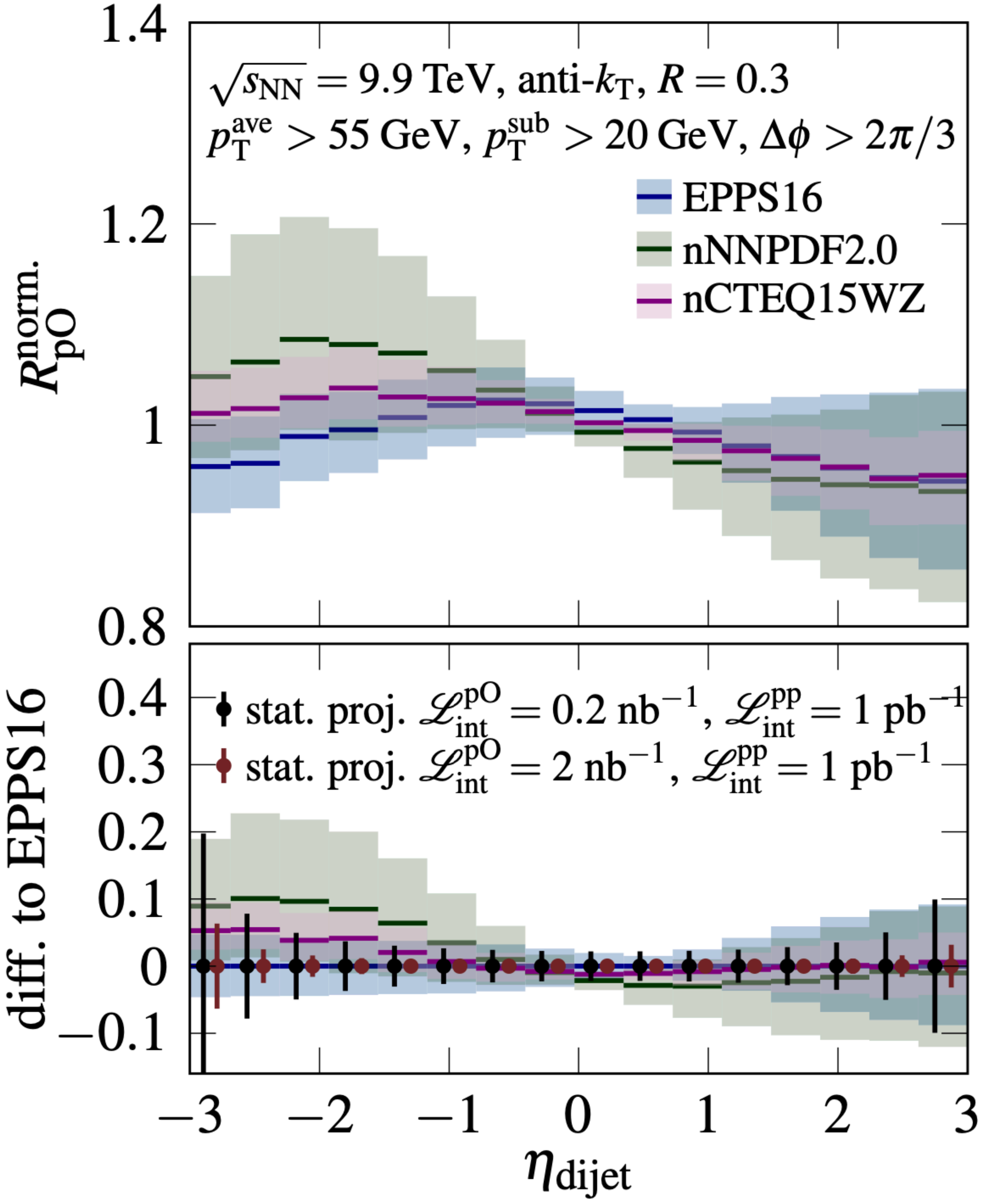
- ➔ Direct access to nuclear modifications

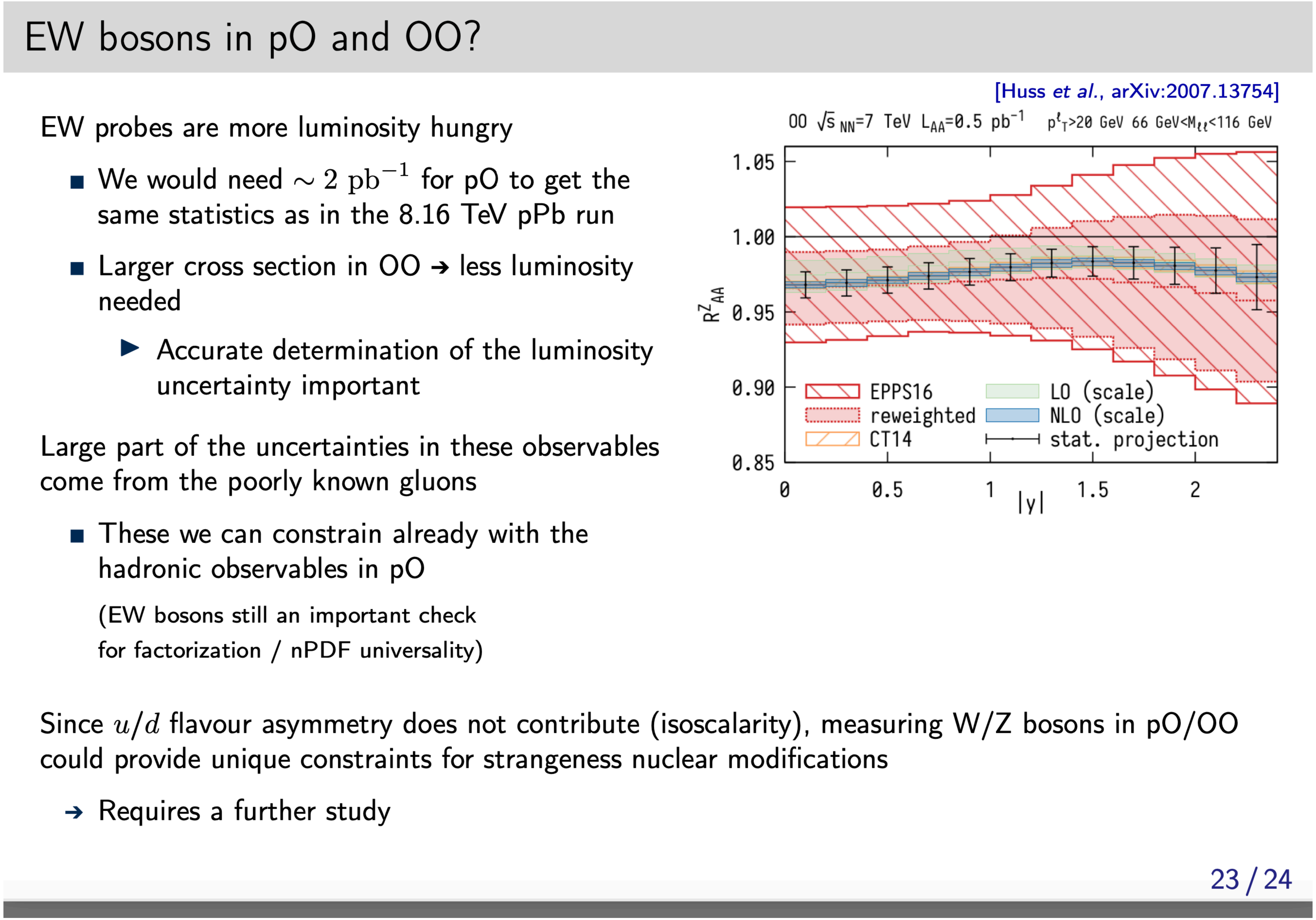
Luminosity (and hadronization) uncertainties also (expected to) cancel!

Already $\sim 1\ \mathrm{nb}^{-1}$ can be expected to be enough to put new constraints on nPDFs (if we have sufficient statistics for the pp reference)

- ➔ Can resolve different nPDF parametrisations!
- ➔ We would heavily benefit from having the pp reference!

The expected $2\ \mathrm{nb}^{-1}$ for LHCb should be enough to give small-x gluon constraints also from forward D-meson production!





EW bosons in pO and OO?

[Huss *et al.*, arXiv:2007.13754]

EW probes are more luminosity hungry

- We would need $\sim 2\ \mathrm{pb}^{-1}$ for pO to get the same statistics as in the 8.16 TeV pPb run
- Larger cross section in OO ➔ less luminosity needed
  - Accurate determination of the luminosity uncertainty important

Large part of the uncertainties in these observables come from the poorly known gluons

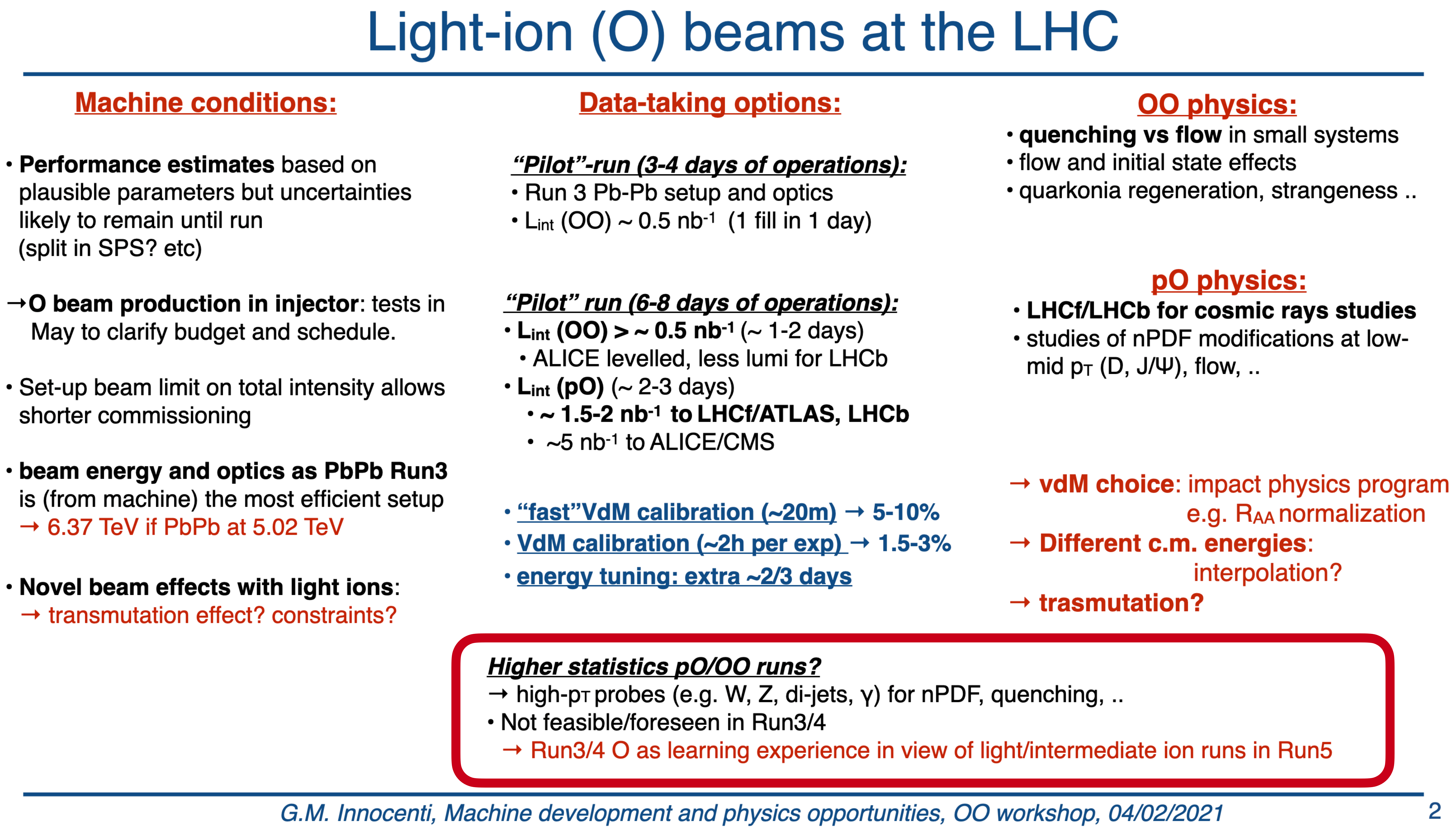
- These we can constrain already with the hadronic observables in pO

  (EW bosons still an important check for factorization / nPDF universality)

Since u/d flavour asymmetry does not contribute (isoscalarity), measuring W/Z bosons in pO/OO could provide unique constraints for strangeness nuclear modifications

➔ Requires a further study

Petja Paakkinen, Opportunities of OO and pO collisions at the LHC (2021), link



Light-ion (O) beams at the LHC

Machine conditions:

- **Performance estimates** based on plausible parameters but uncertainties likely to remain until run (split in SPS? etc)

→**O beam production in injector**: tests in May to clarify budget and schedule.

- Set-up beam limit on total intensity allows shorter commissioning
- **beam energy and optics as PbPb Run3** is (from machine) the most efficient setup
  → 6.37 TeV if PbPb at 5.02 TeV
- **Novel beam effects with light ions**:
  → transmutation effect? constraints?

Data-taking options:

"Pilot"-run (3-4 days of operations):

- Run 3 Pb-Pb setup and optics
- L_{int} (OO) ~ 0.5 nb^{-1} (1 fill in 1 day)

"Pilot" run (6-8 days of operations):

- **L_{int} (OO) > ~ 0.5 nb^{-1}** (~ 1-2 days)
  - ALICE levelled, less lumi for LHCb
- **L_{int} (pO)** (~ 2-3 days)
  - **~ 1.5-2 nb^{-1} to LHCf/ATLAS, LHCb**
  - ~5 nb^{-1} to ALICE/CMS

- **"fast"VdM calibration (~20m) → 5-10%**
- **VdM calibration (~2h per exp) → 1.5-3%**
- **energy tuning: extra ~2/3 days**

OO physics:

- **quenching vs flow** in small systems
- flow and initial state effects
- quarkonia regeneration, strangeness ..

pO physics:

- **LHCf/LHCb for cosmic rays studies**
- studies of nPDF modifications at low-mid p_T (D, J/Ψ), flow, ..

→ **vdM choice**: impact physics program e.g. R_{AA} normalization
→ **Different c.m. energies**: interpolation?
→ **trasmutation?**

Higher statistics pO/OO runs?
→ high-p_T probes (e.g. W, Z, di-jets, γ) for nPDF, quenching, ..
- Not feasible/foreseen in Run3/4
  → Run3/4 O as learning experience in view of light/intermediate ion runs in Run5

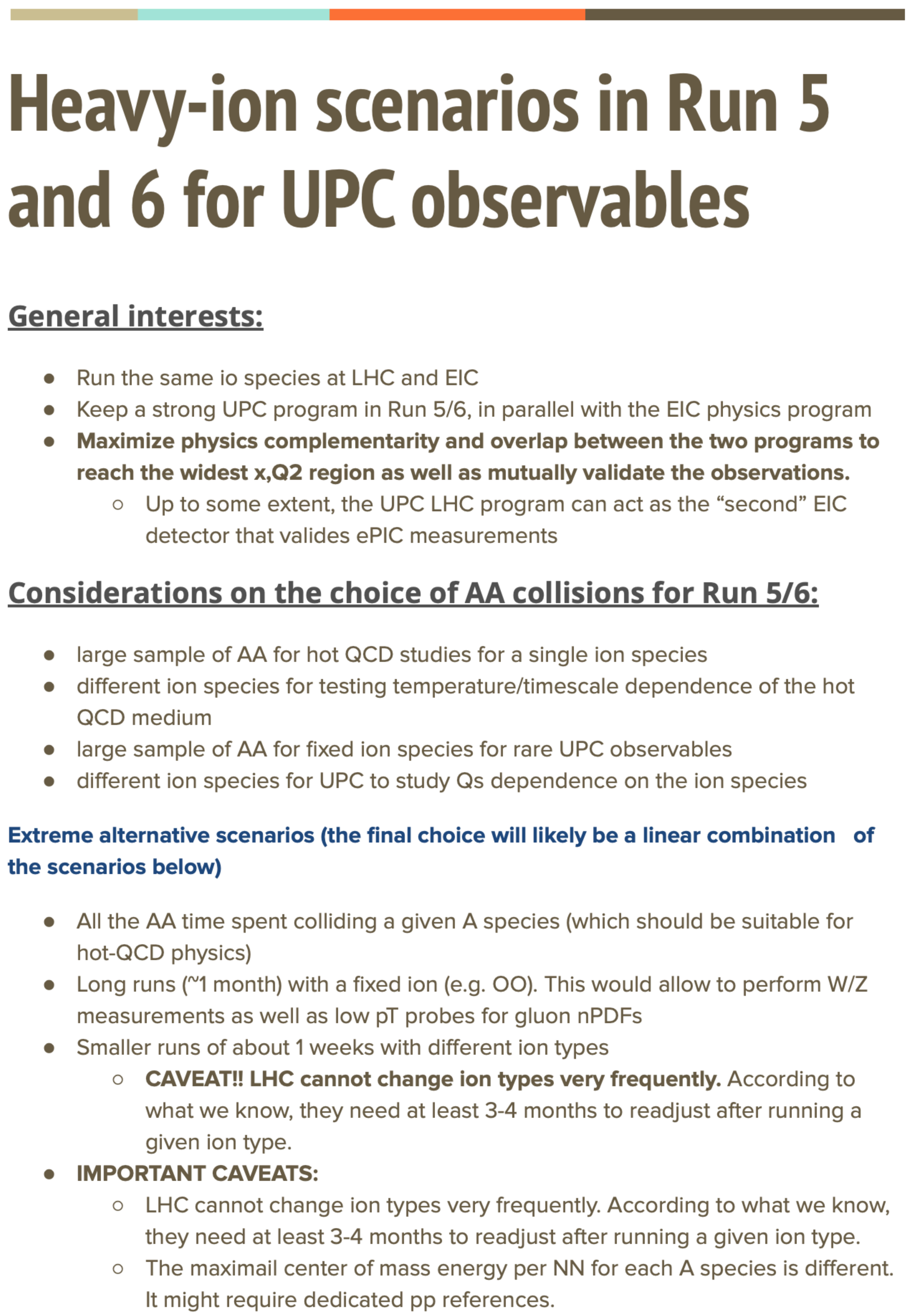
G.M. Innocenti, Machine development and physics opportunities, OO workshop, 04/02/2021

G.M. Innocenti, Opportunities of OO and pO collisions at the LHC (2021), https://indico.cern.ch/event/975877/

Ideas/discussions (focus on Run5/6)

UPC program with pp, pA, and AA collisions at the LHC in parallel with ep/eA measurements at the EIC (LHC Run5 and 6)

GOOGLE DOC TO COLLECT INPUTS:
https://docs.google.com/document/d/1aul1fPSdyMKM2250Q1sbfPy-3b5AcEisKCsy4VlsdoA/edit?usp=sharing



Heavy-ion scenarios in Run 5 and 6 for UPC observables

General interests:

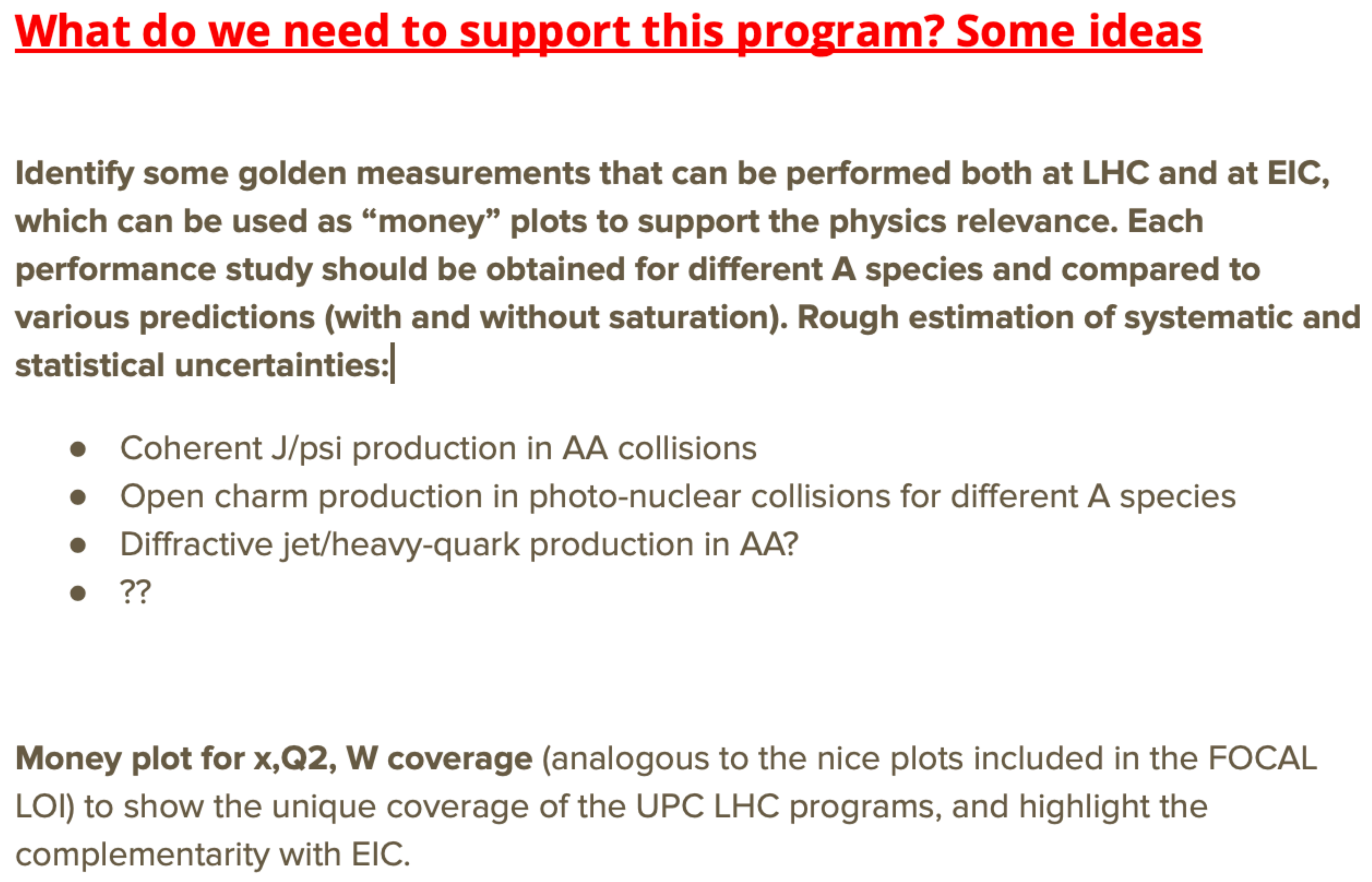
- Run the same io species at LHC and EIC
- Keep a strong UPC program in Run 5/6, in parallel with the EIC physics program
- **Maximize physics complementarity and overlap between the two programs to reach the widest x,Q2 region as well as mutually validate the observations.**
  - Up to some extent, the UPC LHC program can act as the "second" EIC detector that valides ePIC measurements

Considerations on the choice of AA collisions for Run 5/6:

- large sample of AA for hot QCD studies for a single ion species
- different ion species for testing temperature/timescale dependence of the hot QCD medium
- large sample of AA for fixed ion species for rare UPC observables
- different ion species for UPC to study Qs dependence on the ion species

Extreme alternative scenarios (the final choice will likely be a linear combination of the scenarios below)

- All the AA time spent colliding a given A species (which should be suitable for hot-QCD physics)
- Long runs (~1 month) with a fixed ion (e.g. OO). This would allow to perform W/Z measurements as well as low pT probes for gluon nPDFs
- Smaller runs of about 1 weeks with different ion types
  - **CAVEAT!! LHC cannot change ion types very frequently.** According to what we know, they need at least 3-4 months to readjust after running a given ion type.
- **IMPORTANT CAVEATS:**
  - LHC cannot change ion types very frequently. According to what we know, they need at least 3-4 months to readjust after running a given ion type.
  - The maximail center of mass energy per NN for each A species is different. It might require dedicated pp references.



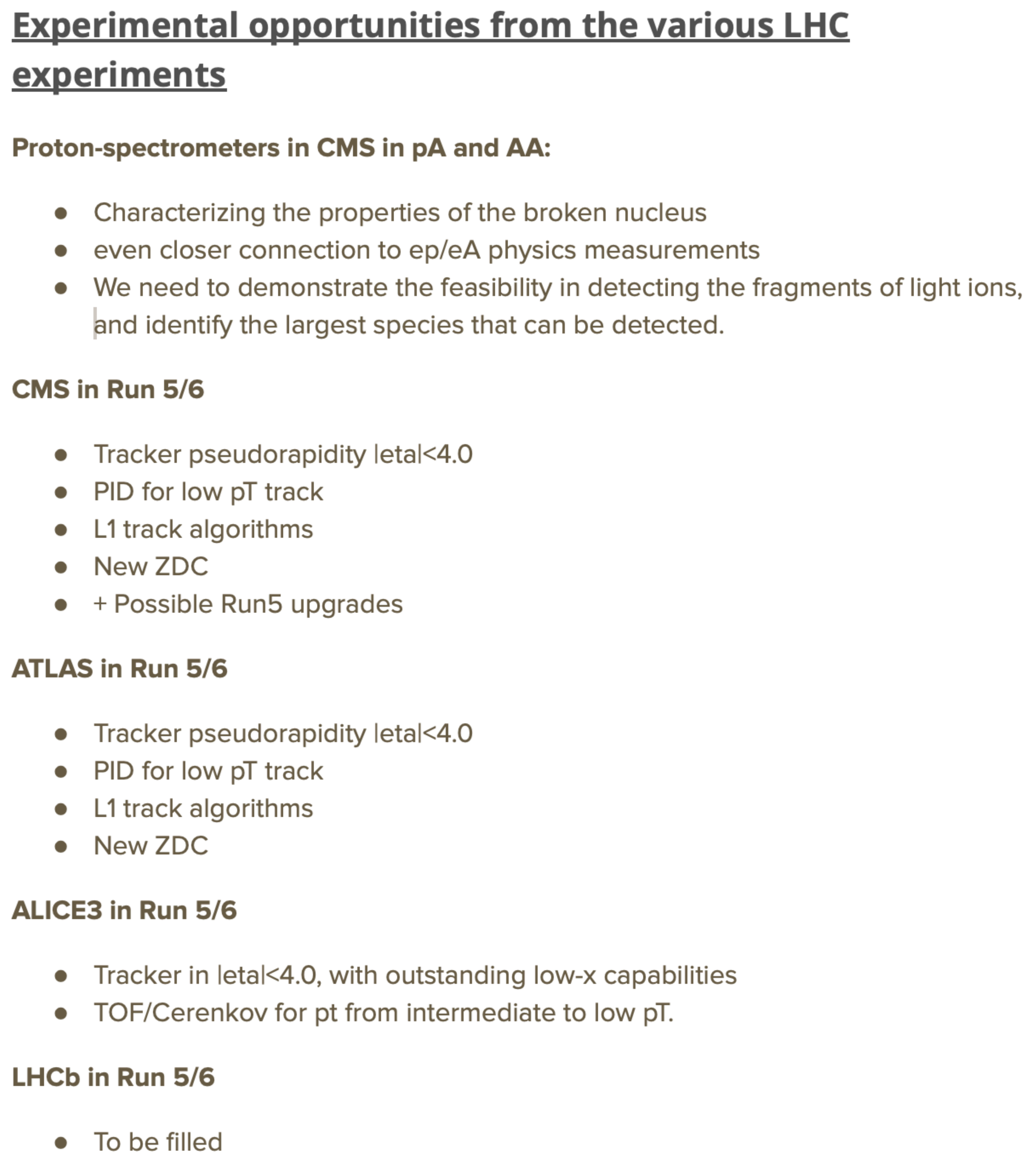
What do we need to support this program? Some ideas

Identify some golden measurements that can be performed both at LHC and at EIC, which can be used as "money" plots to support the physics relevance. Each performance study should be obtained for different A species and compared to various predictions (with and without saturation). Rough estimation of systematic and statistical uncertainties:

- Coherent J/psi production in AA collisions
- Open charm production in photo-nuclear collisions for different A species
- Diffractive jet/heavy-quark production in AA?
- ??

Money plot for x,Q2, W coverage (analogous to the nice plots included in the FOCAL LOI) to show the unique coverage of the UPC LHC programs, and highlight the complementarity with EIC.

GOOGLE DOC TO COLLECT INPUTS:
https://docs.google.com/document/d/1aul1fPSdyMKM2250Q1sbfPy-3b5AcEisKCsy4VlsdoA/edit?usp=sharing



Experimental opportunities from the various LHC experiments

Proton-spectrometers in CMS in pA and AA:

- Characterizing the properties of the broken nucleus
- even closer connection to ep/eA physics measurements
- We need to demonstrate the feasibility in detecting the fragments of light ions, and identify the largest species that can be detected.

CMS in Run 5/6

- Tracker pseudorapidity $|eta|<4.0$
- PID for low pT track
- L1 track algorithms
- New ZDC
- + Possible Run5 upgrades

ATLAS in Run 5/6

- Tracker pseudorapidity $|eta|<4.0$
- PID for low pT track
- L1 track algorithms
- New ZDC

ALICE3 in Run 5/6

- Tracker in $|eta|<4.0$, with outstanding low-x capabilities
- TOF/Cerenkov for pt from intermediate to low pT.

LHCb in Run 5/6

- To be filled

GOOGLE DOC TO COLLECT INPUTS:
https://docs.google.com/document/d/1aul1fPSdyMKM2250Q1sbfPy-3b5AcEisKCsy4VlsdoA/edit?usp=sharing

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