Quark Matter 2015
Kobe, September 29th 2015

Nuclear collisions at the Future Circular Collider

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Contents:

1. The FCC(-AA):
   - Motivation.
   - Site.
   - Parameters.
   - Detector.

2. Physics case:
   - Global observables.
   - Hard probes.
   - Small x.

3. Summary and outlook.

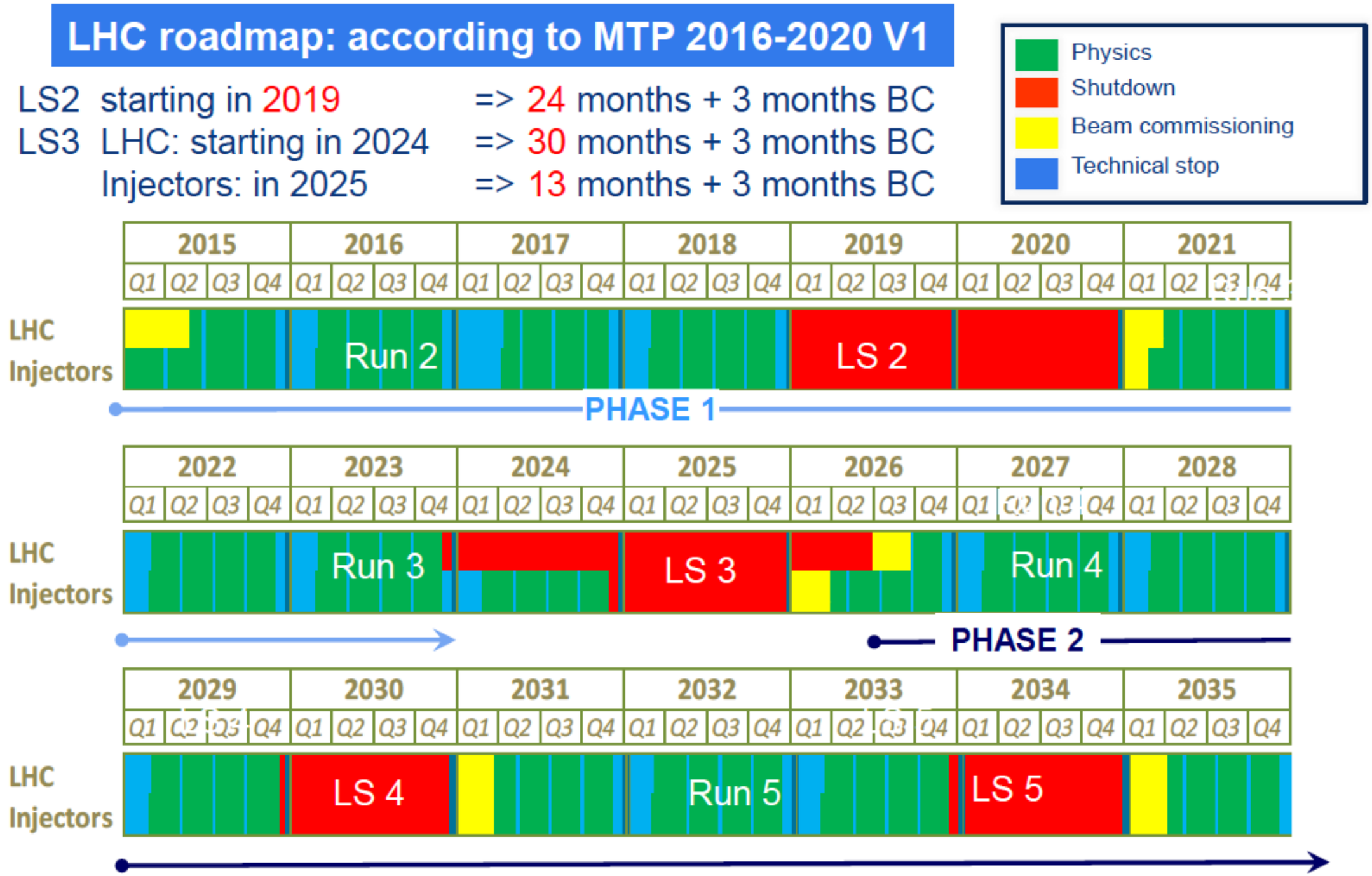
➜ Kickoff workshop, Geneva, Feb. 2014: https://indico.cern.ch/event/282344/;
➜ A. Dainese in QM2014, https://indico.cern.ch/event/219436/session/20/contribution/480/material/slides/0.pdf, 1407.7649;
➜ 4 HI dedicated workshops, last one at CERN 09.14: https://indico.cern.ch/event/331669/;
➜ Workshop, ECT* 03.15: https://indico.cern.ch/event/382529/;
➜ FCC Week 2015, Washington DC, Mar. 2015: http://indico.cern.ch/event/340703/timetable/#all.detailed;

➜ https://fcc.web.cern.ch/.
➜ https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons.

Motivation:

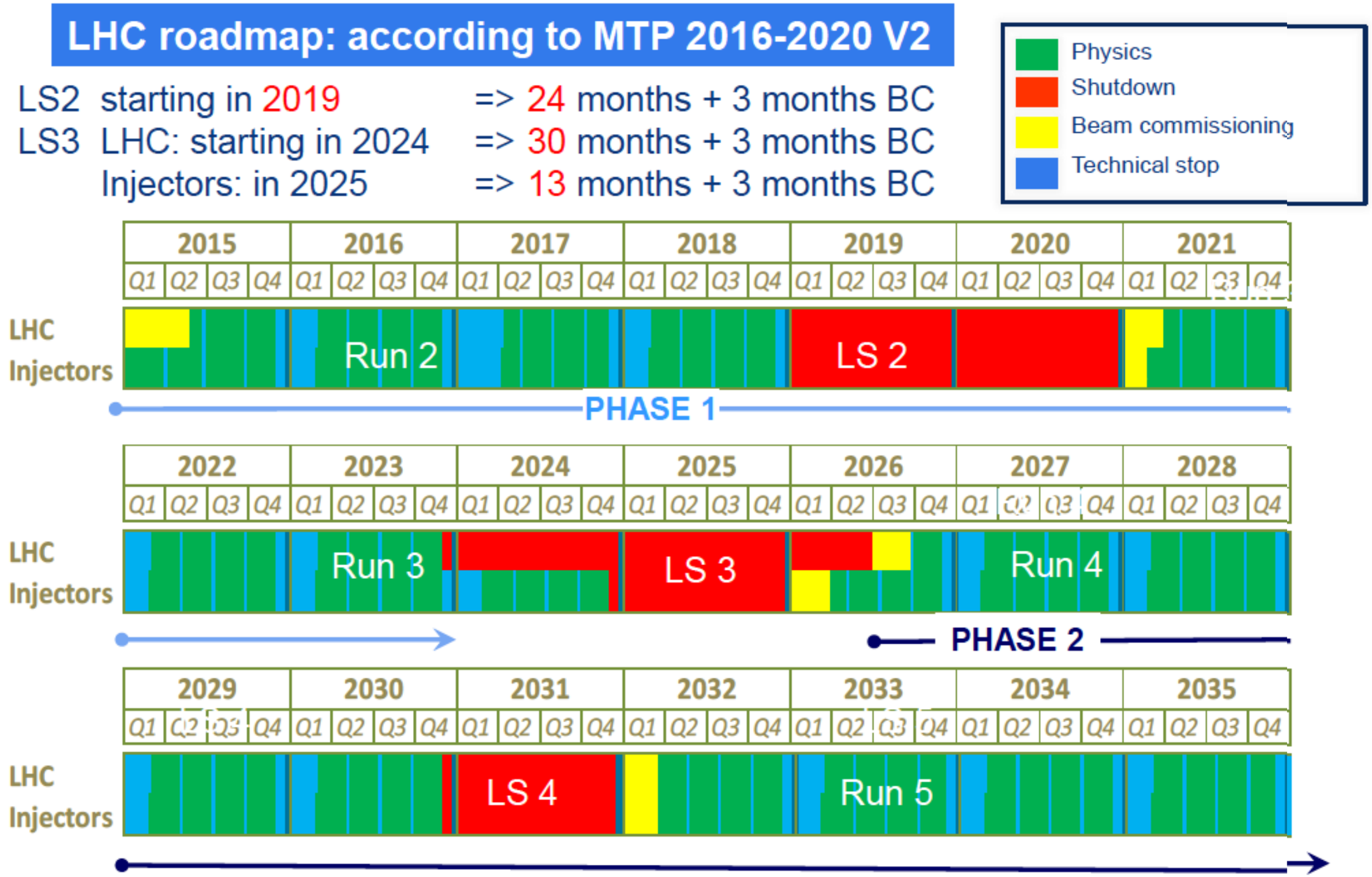
- Big machines take long time to come from first idea to reality e.g. >20 years for the LHC, so it is time to start thinking of another high-energy machine after the LHC.

Motivation:



Frederick Bordry to the SPC and FC, June 2015

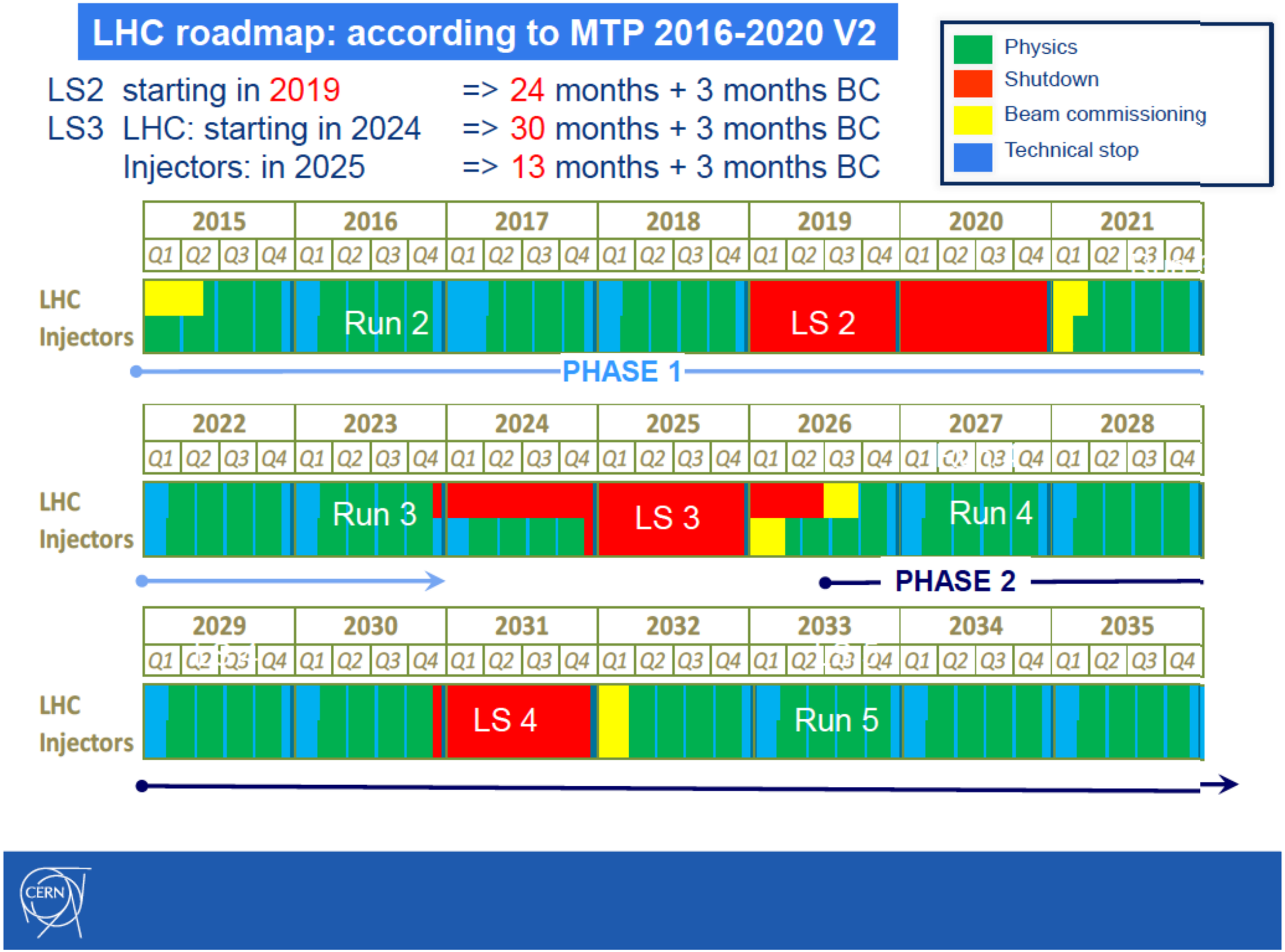
Motivation:



Frederick Bordry to the SPC and FC, June 2015

Motivation:

Goal of HI program: 10-15 nb^{-1} in Run3+4.



Frederick Bordry to the SPC and FC, June 2015

Site:

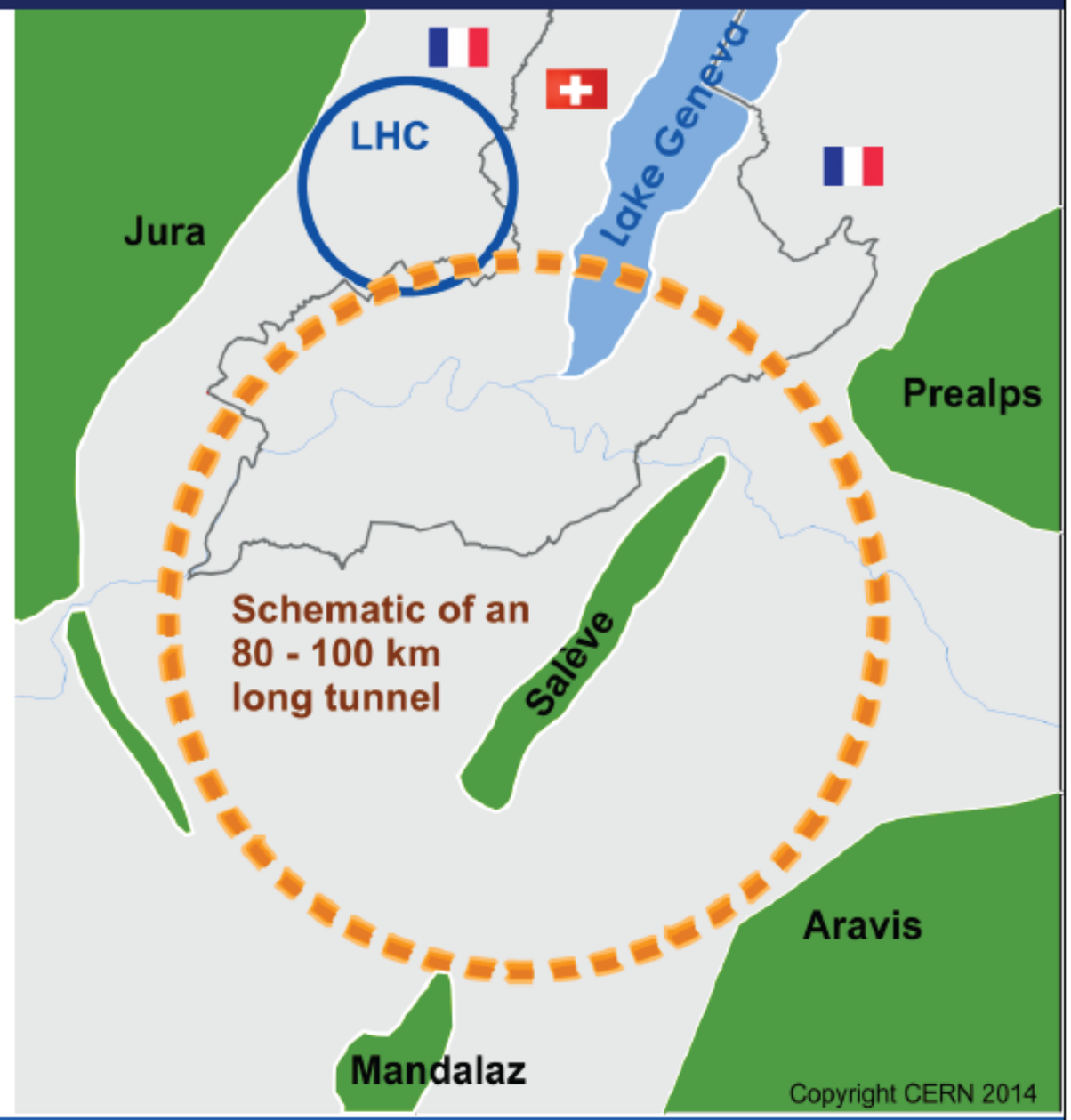
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km
  ~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
  120-350 GeV
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



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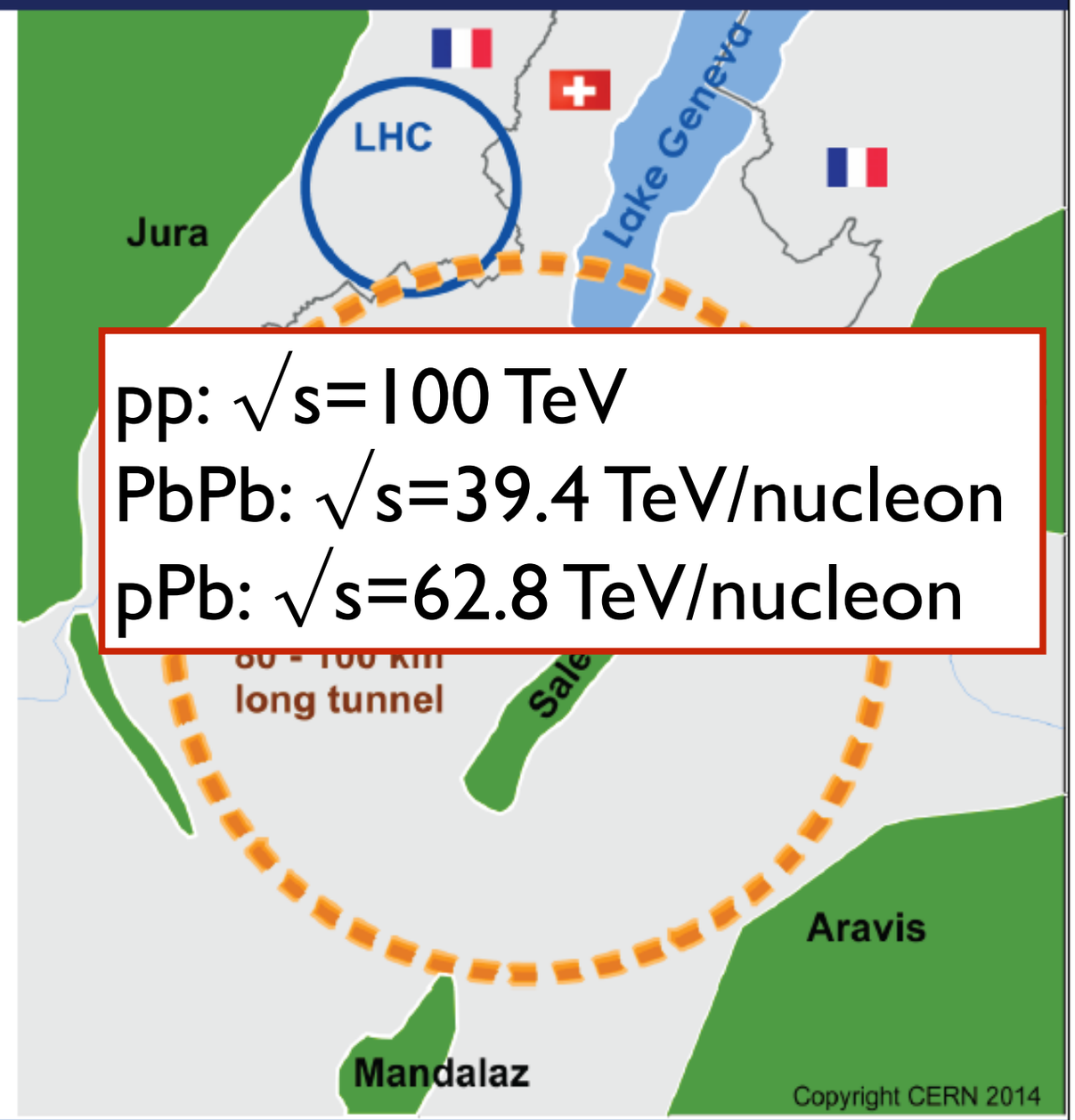


pp: $\sqrt{s}$=100 TeV
PbPb: $\sqrt{s}$=39.4 TeV/nucleon
pPb: $\sqrt{s}$=62.8 TeV/nucleon

Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
5

Site:

93 km option (Lebrun in Washington DC)

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°):	-15
Slope Angle x-x(%):	.3
Slope Angle y-y(%):	0

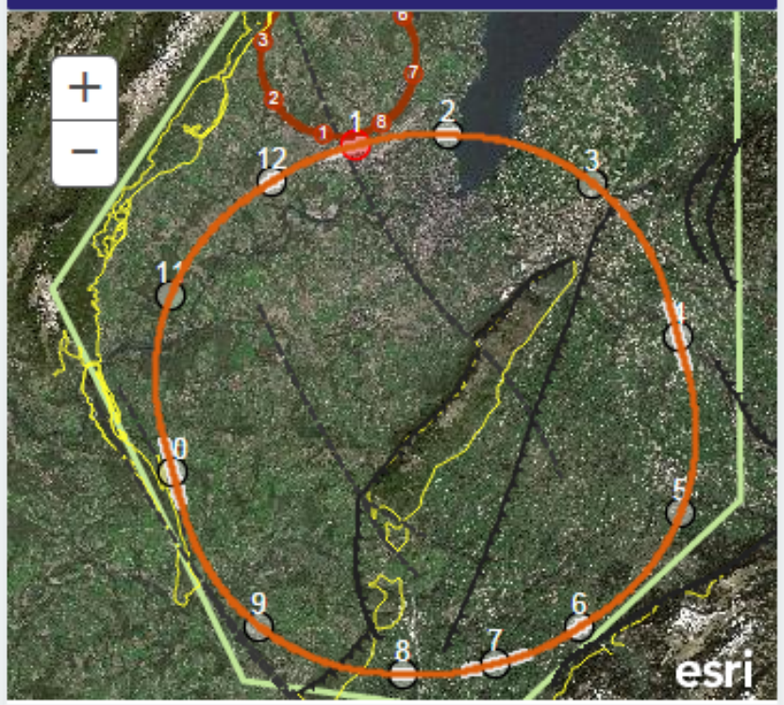
CALCULATE

Alignment centre

X: 2498923 Y: 1106695

LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

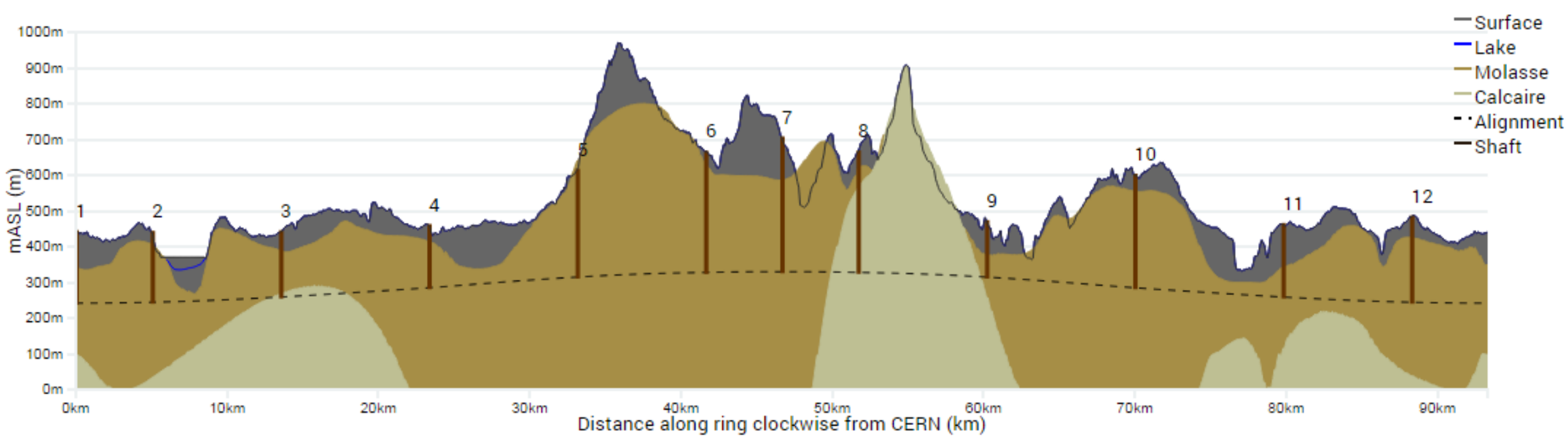
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

Alignment Profile



Site:

100 km option (Lebrun in Washington DC)

Alignment | **Shaft Tools**

Choose alignment option

100km quasi-circular

Tunnel depth at centre: 263mASL

Gradient Parameters

Azimuth (°): -20

Slope Angle x-x(%): .65

Slope Angle y-y(%): 0

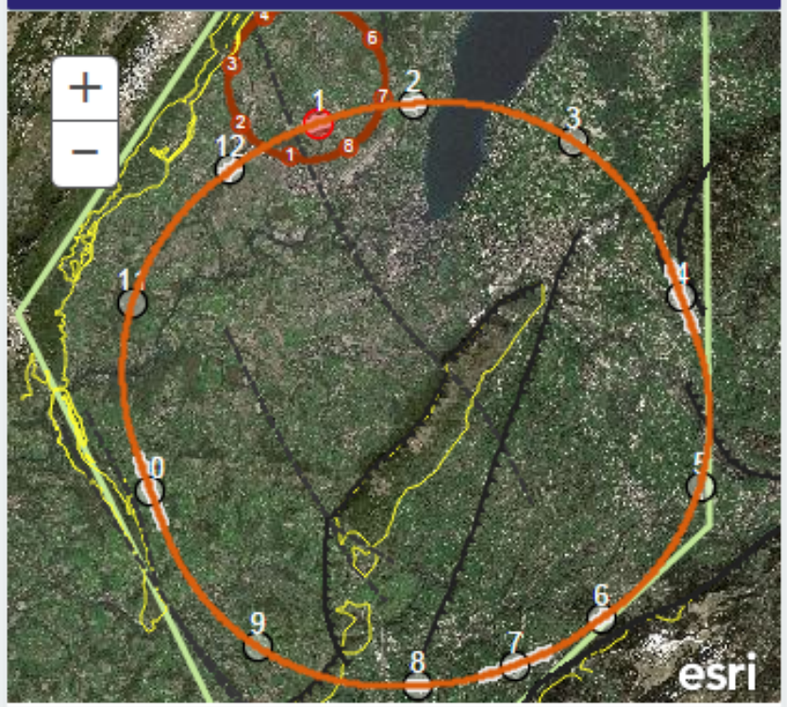
CALCULATE

Alignment centre

X: 2500119 Y: 1108575

LHC Intersection	IP 1	IP 2
Angle	-65°	65°
Depth	221m	180m

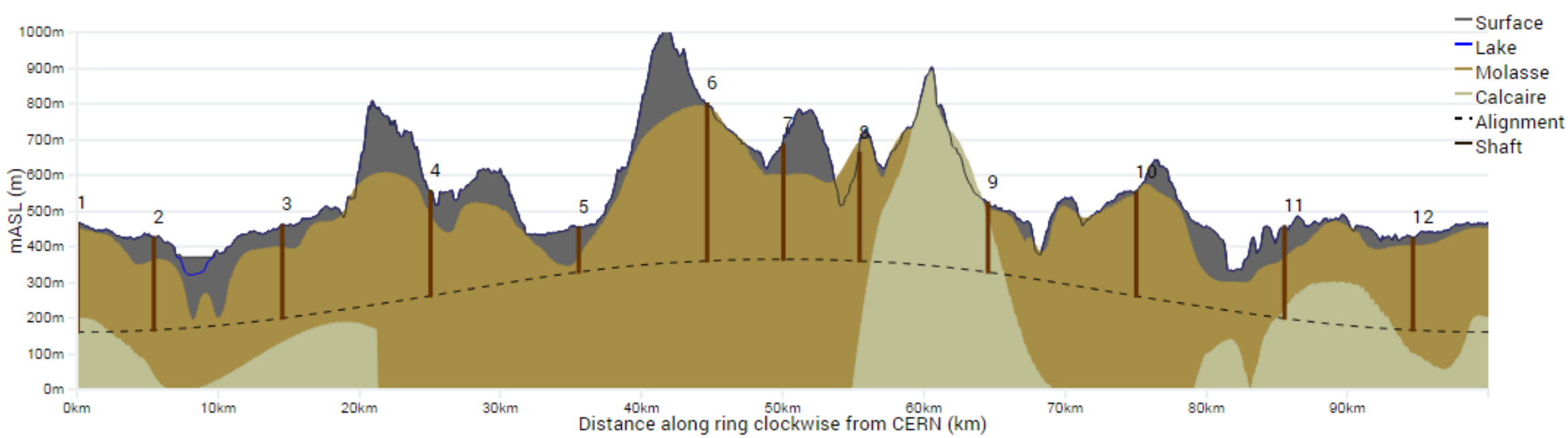
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	304	303	305	306	16	248	40
2	260	260	263	271	65	195	0
3	261	249	258	262	62	199	0
4	293	269	296	322	64	229	0
5	125	124	127	129	85	40	0
6	440	432	441	451	10	431	0
7	321	302	332	368	85	235	0
8	302	235	304	358	0	333	0
9	195	184	195	204	15	18	161
10	291	289	296	307	7	285	0
11	257	247	252	257	89	149	19
12	259	258	262	266	23	236	0
Total	3309	3152	3331	3501	521	2597	220

Alignment Profile



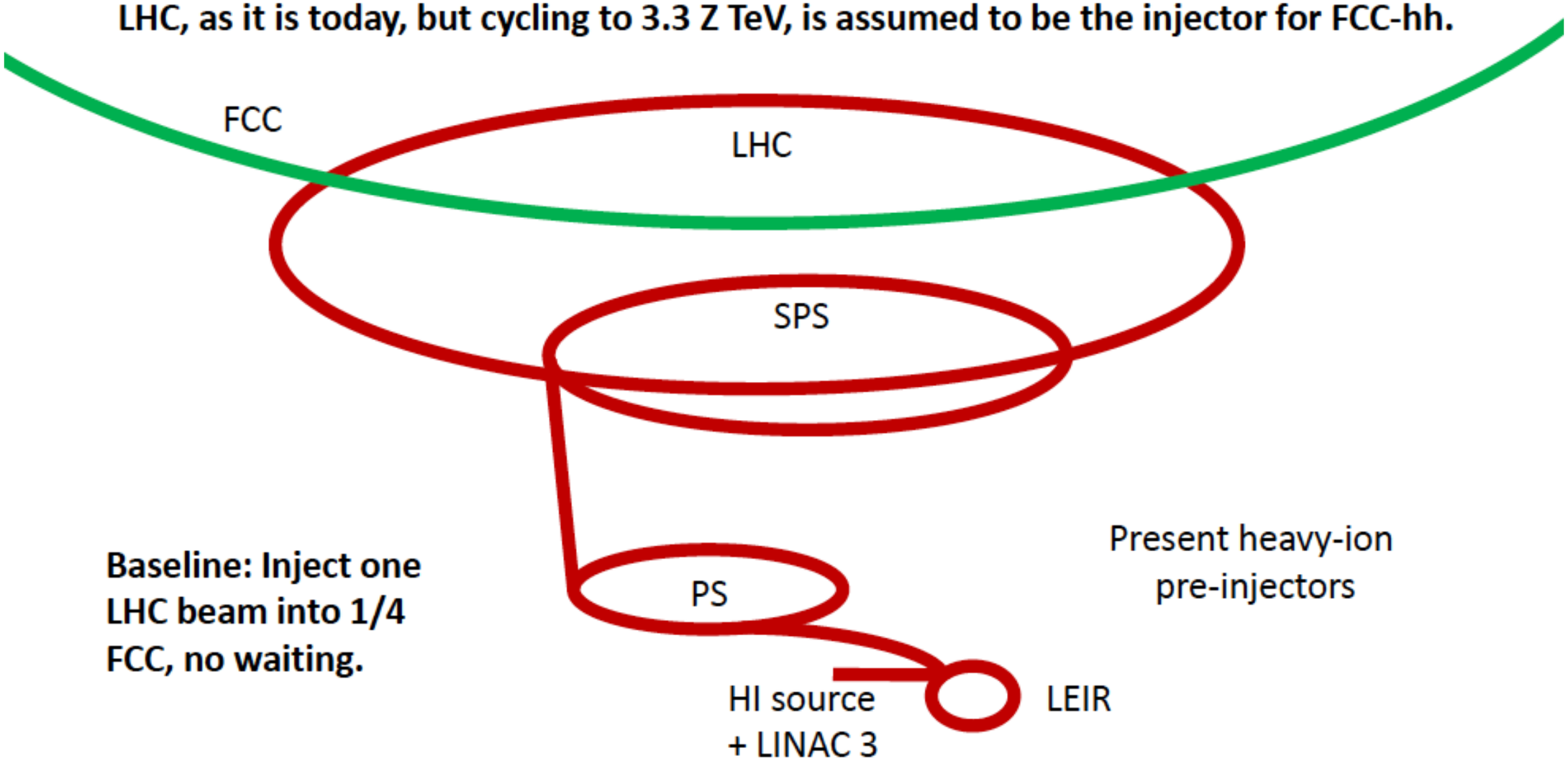
Accelerator parameters:

Heavy Ion Pre-Accelerator Chain

The requirements and performance of the pre-accelerator chain for FCC are under studied.

R&D

Straw-man assumption to estimate (conservative) beam parameters and luminosity:
LHC, as it is today, but cycling to 3.3 Z TeV, is assumed to be the injector for FCC-hh.



Baseline: Inject one LHC beam into 1/4 FCC, no waiting.

Accelerator parameters:

Conservative filling scheme!!!

	Unit	LHC Design	FCC Collision	FCC Collision
Luminosity				
Operation mode	-	Pb-Pb	Pb-Pb	p-Pb
β-function at the IP	[m]	0.5	1.1	
Initial RMS beam size at IP	[μm]	15.9	8.8	
Initial luminosity	[Hz/mb]	1	2.6	213
Peak luminosity	[Hz/mb]	1	7.3	1192
Integrated luminosity per fill	[μb^{-1}]	<15	57.8	21068
Integrated luminosity per run	[nb^{-1}]	-	8.3	1784
Initial bb tune shift per IP	[10^{-4}]	1.8	3.7	3.7
Total cross-section	[b]	515	597	2
Peak BFPP beam power	[W]	26	1705	0
Initial beam current lifetime	[h]	<11.2 (2 exp.)	10.9	39.3
Luminosity lifetime ($\mathcal{L}_0/e$)	[h]	<5.6 (2 exp.)	6.2	14.0

Schaumann, 1503.09107

Note: the ALICE goal for Run 3+4 is 10-15 nb^{-1} in PbPb; in the 2013 pPb run got ~30 nb^{-1}.

Accelerator parameters:

First (conservative) estimates of luminosity (in comparison with LHC): >8 larger L_{int} per month of running

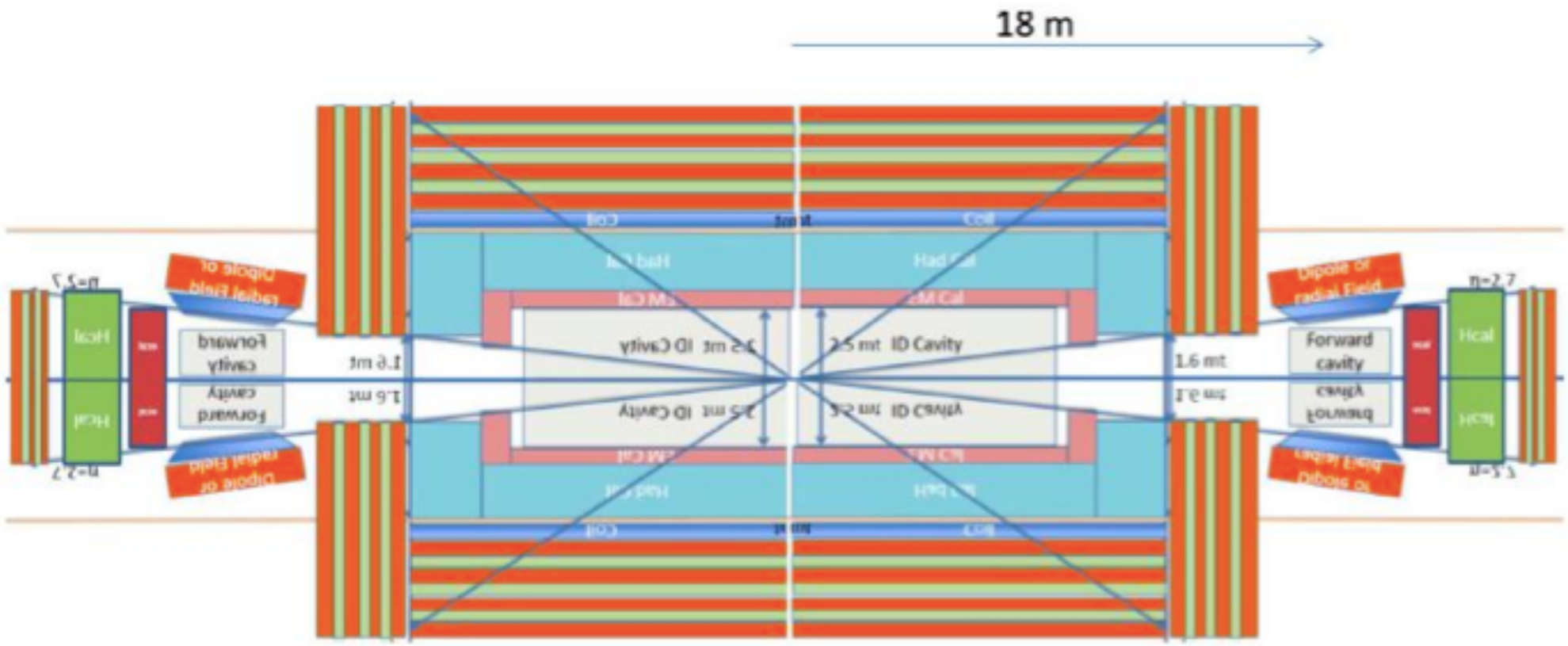
	LHC Run 2 [1]	LHC after LS2 [1]	FHC [2]
Pb–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	(2-3×)10^{27}	5×10^{27}	13×10^{27}
Pb–Pb L_{int} / month (nb^{-1})	0.8(1)	1(1.5)	**>8**
p–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	(2-3×)10^{29}	t.b.d.	3.5×10^{30}
p–Pb L_{int} (nb^{-1})	80	t.b.d.	**>1800**

A. Dainese at ECT*

Could aim for programme of 100/nb (LHC x10)

Detector (pp/pA/AA):

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



Solenoid: 5-6 m diameter, 5-6 T, 23 m long

+ massive Iron yoke for flux return (shielding) and muon tagging.

Dipoles: 10 Tm with return yoke placed at 18 m.

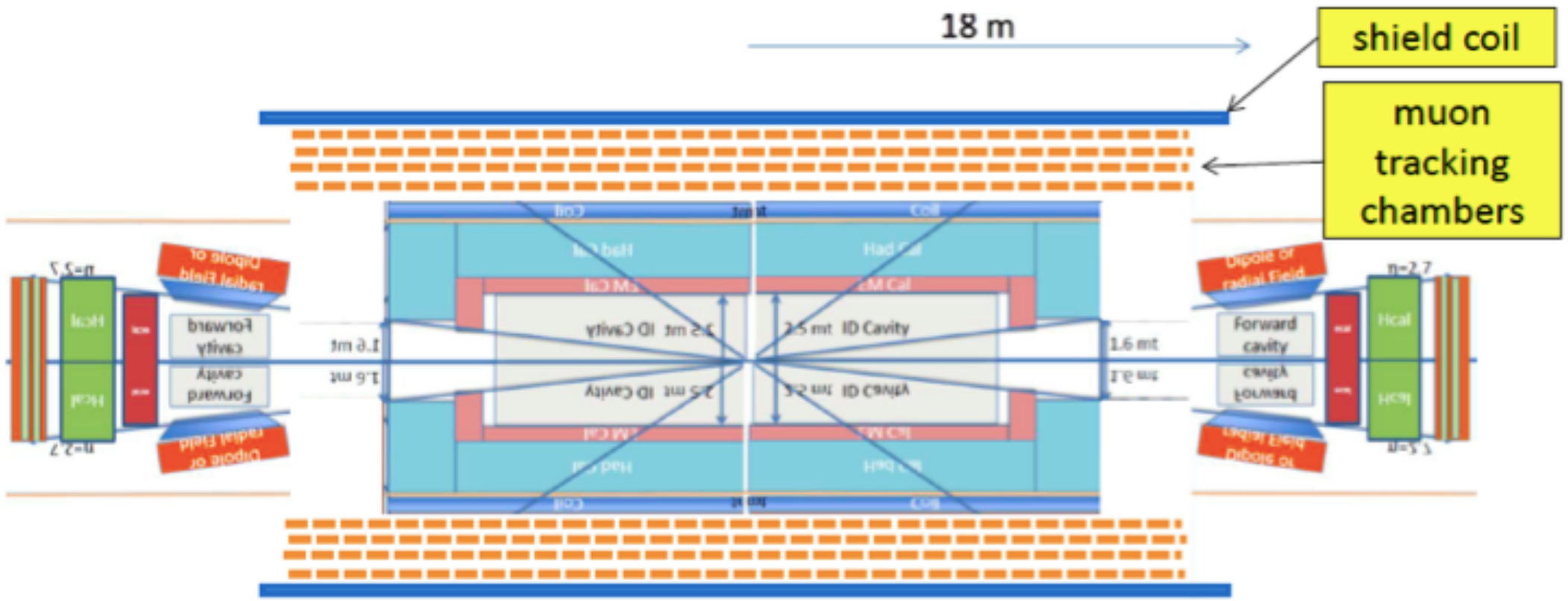
Practically no coupling between dipoles and solenoid.

They can be designed independently at first.

H. Ten Kate

Detector (pp/pA/AA):

Option 2: Twin Solenoid + Dipoles



Twin Solenoid: the original 6 T, 12 m x 23 m solenoid + now with a shielding coil {concept proposed for the 4th detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

Gain?

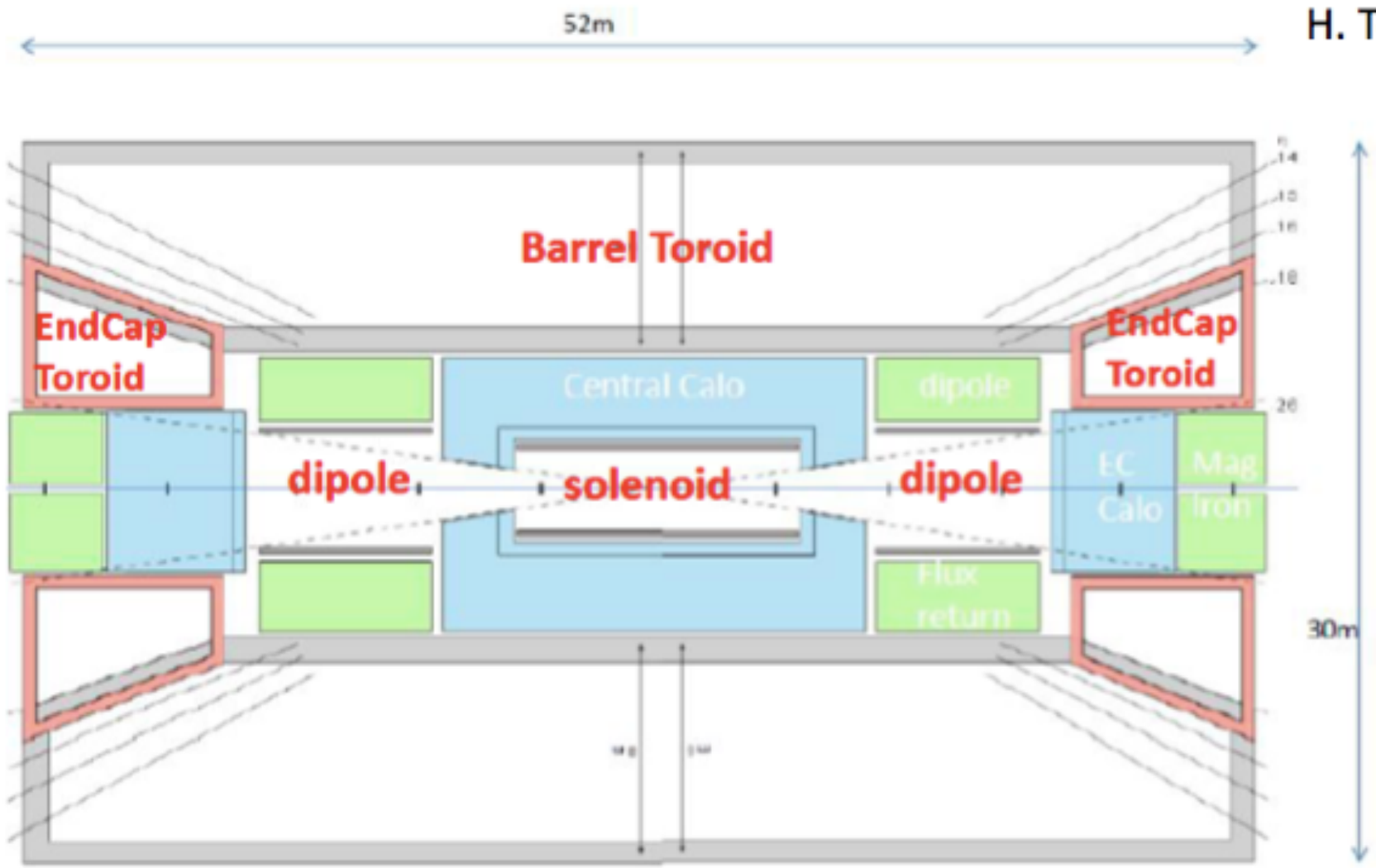
- **+ Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
- **+ Very light:** 2 coils + structures, ≈ 5 kt, only ≈4% of the option with iron yoke!
- **+ Smaller:** outer diameter is less than with iron .

H. Ten Kate

Detector (pp/pA/AA):

Option 3: Toroids + Solenoid + Dipoles (ATLAS +)

H. Ten Kate



- Air core Barrel Toroid with 7 x muon bending power BL^2.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m^3).

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   - Small x.

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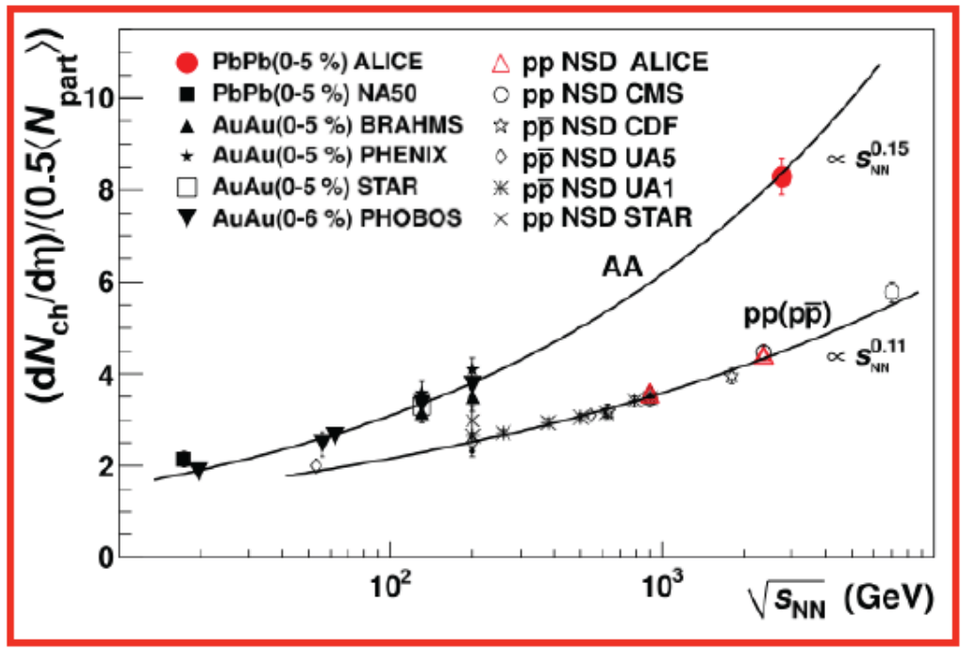
➜ https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons.

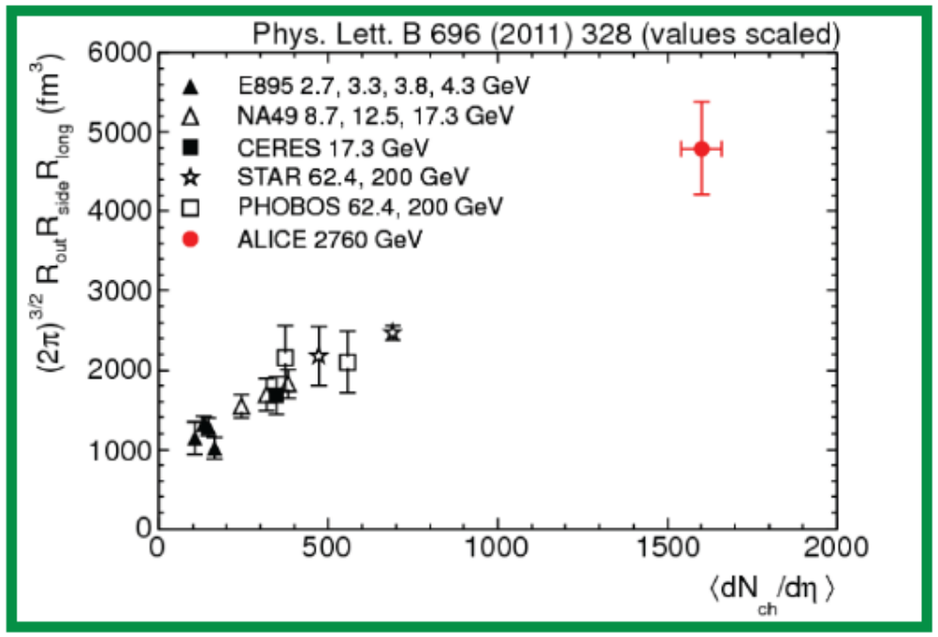
Global properties:

- Using data-driven extrapolations from lower energies to the LHC:

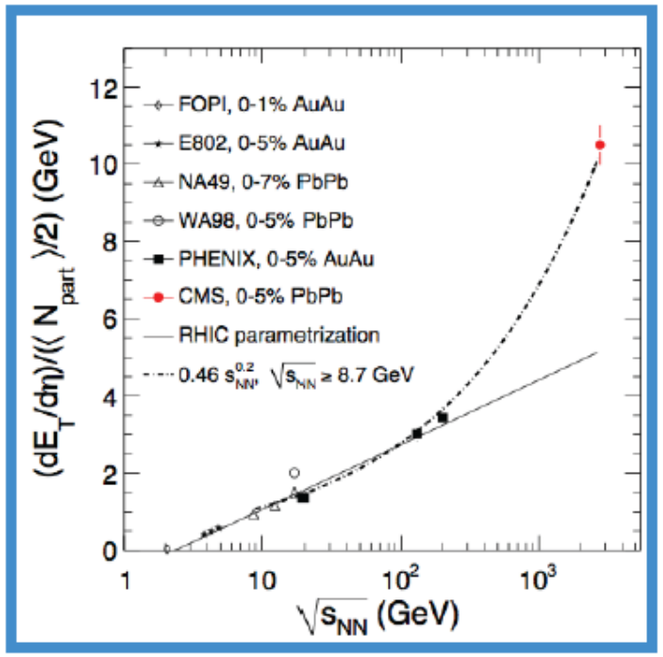
$dN_{ch}/d\eta$ x 1.8



Volume x1.8



$dE_T/d\eta$ x2.2



Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

A. Dainese at QM2014

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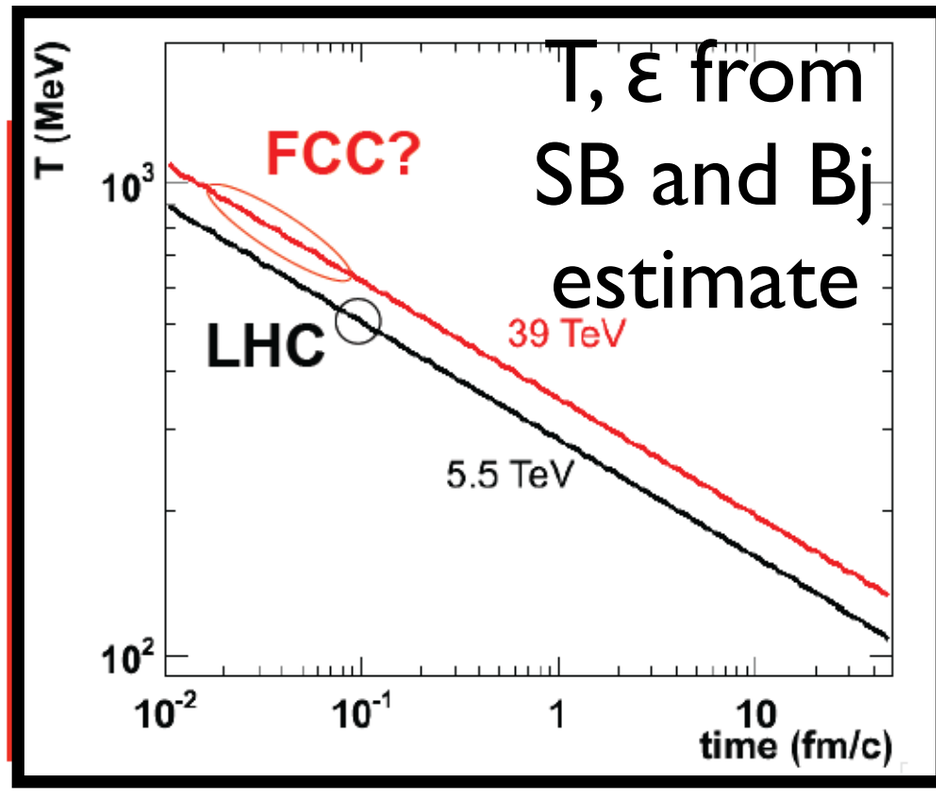

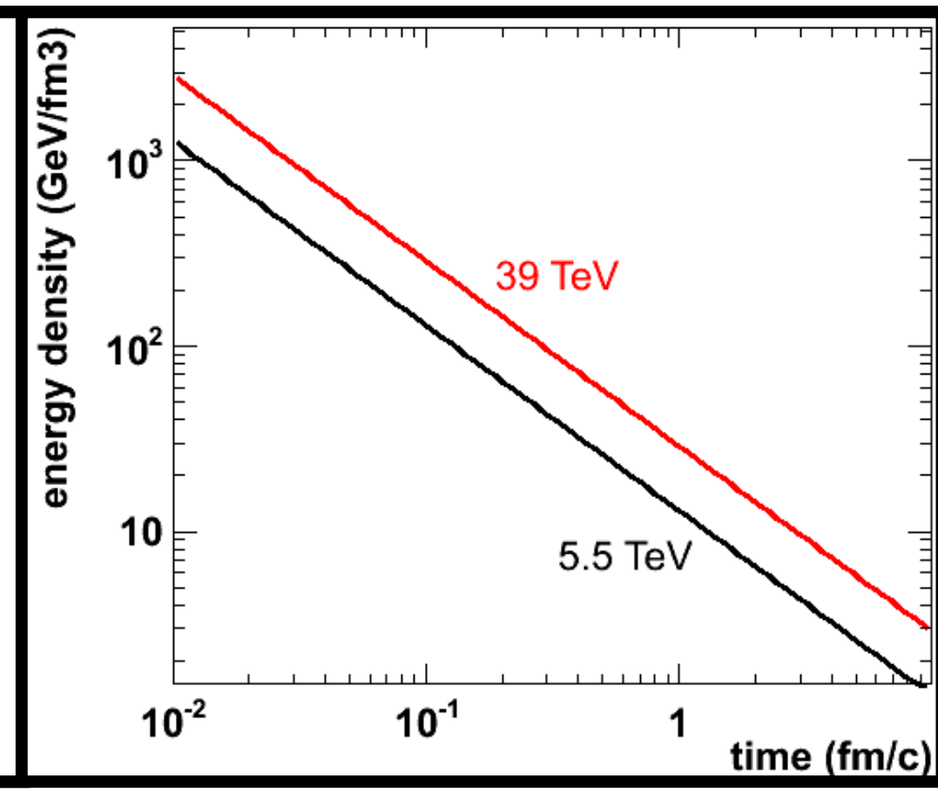

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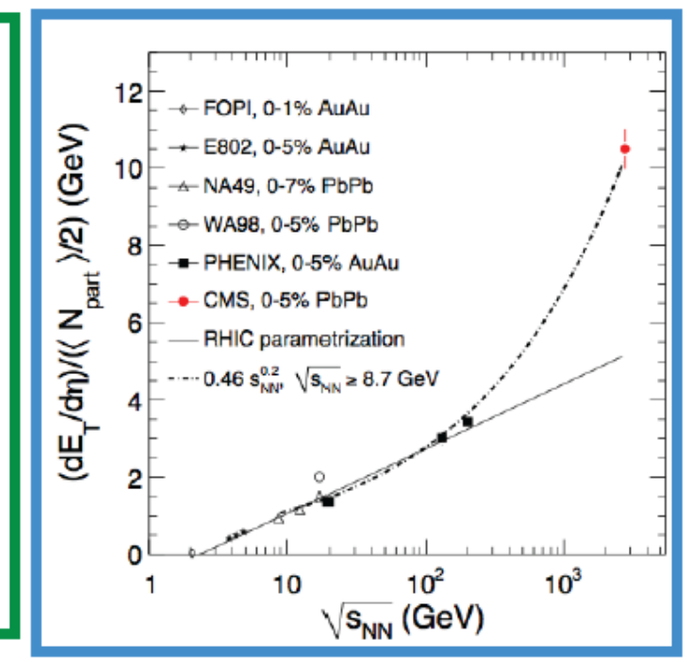

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A. Dainese at QM2014

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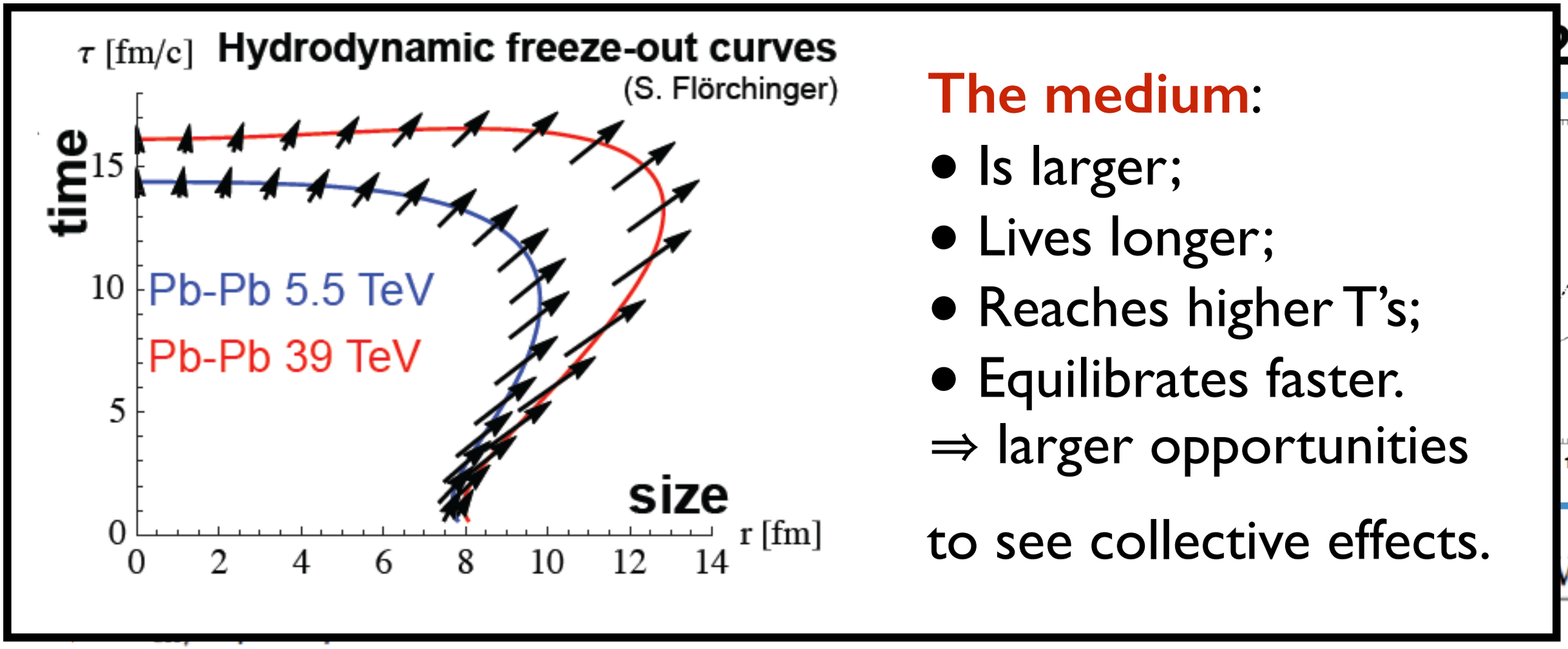

The medium:

- Is larger;
- Lives longer;
- Reaches higher T's;
- Equilibrates faster.

⇒ larger opportunities to see collective effects.

Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
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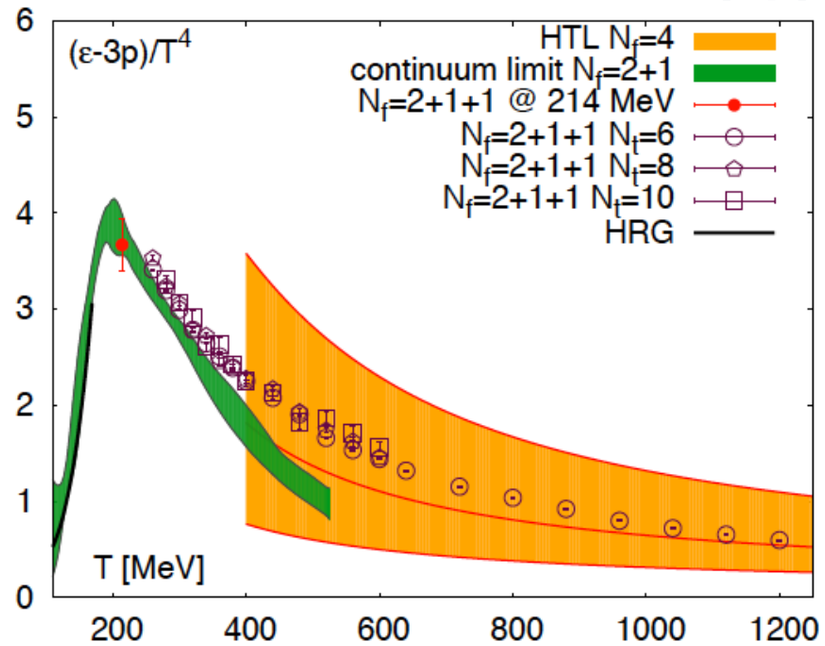
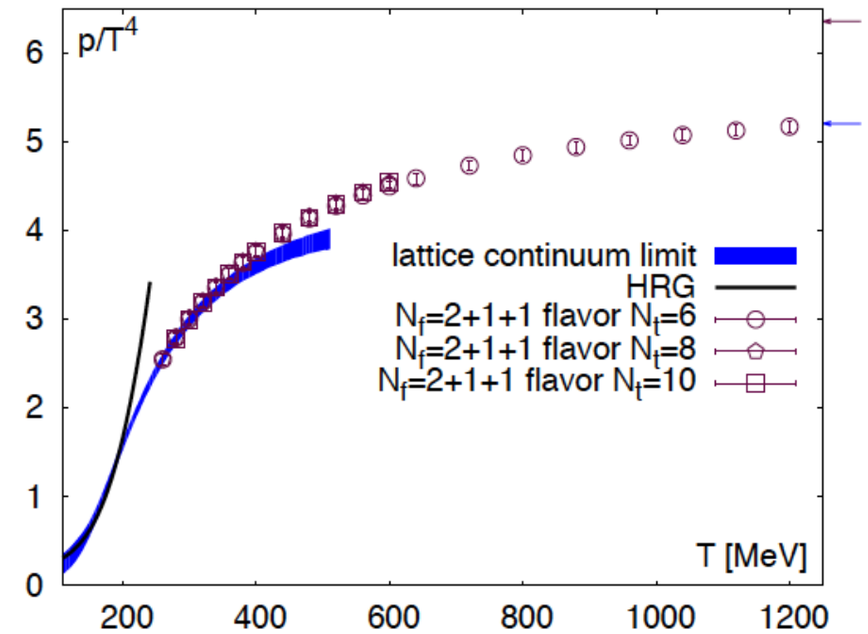
A. Dainese at QM2014

Charm:

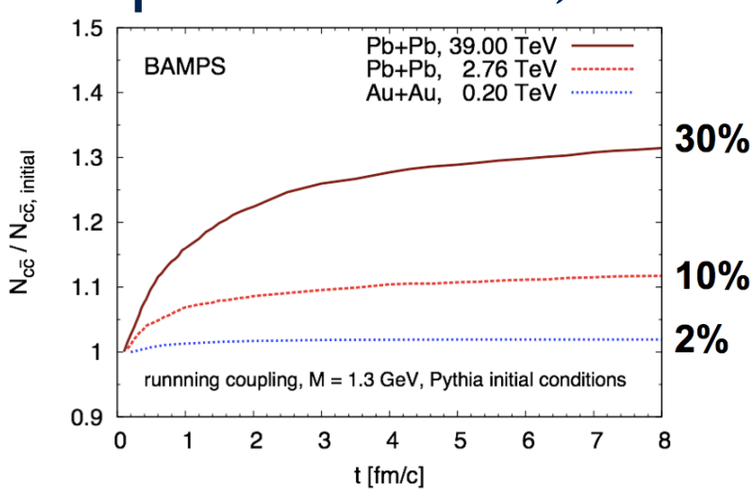
- Charm becomes an active flavour.
- It can be abundantly produced secondary interactions.

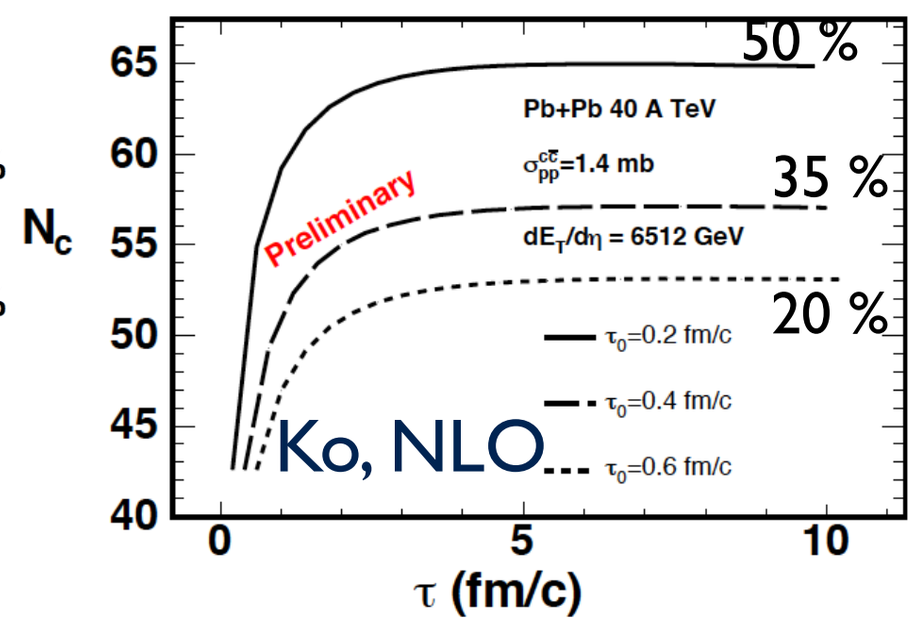
1410.7917

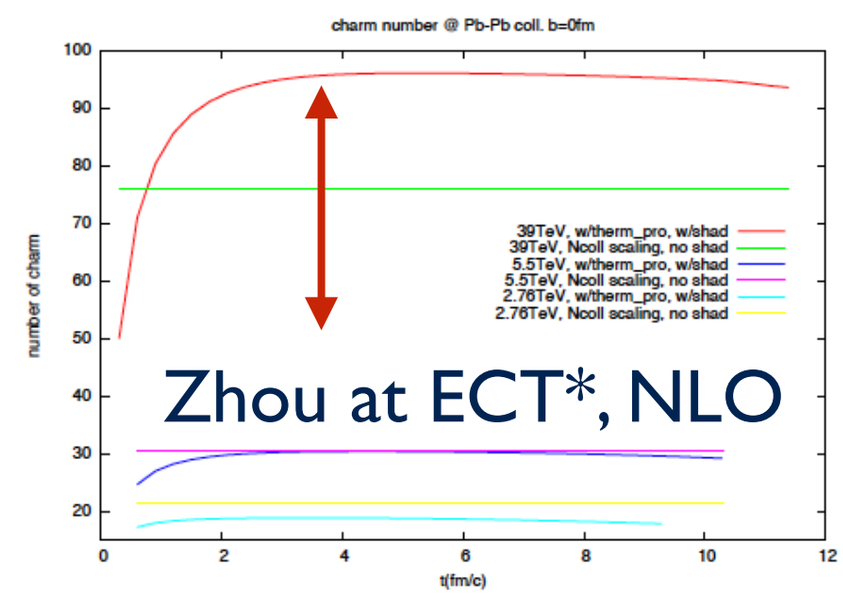




Uphoff at ECT*, LO

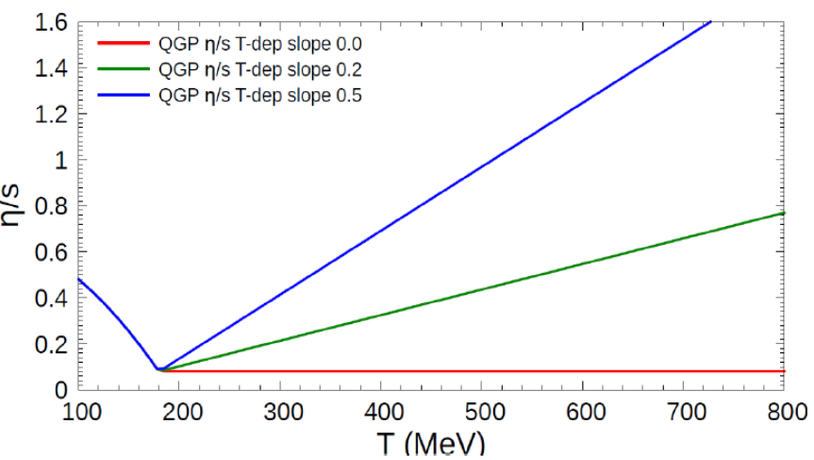




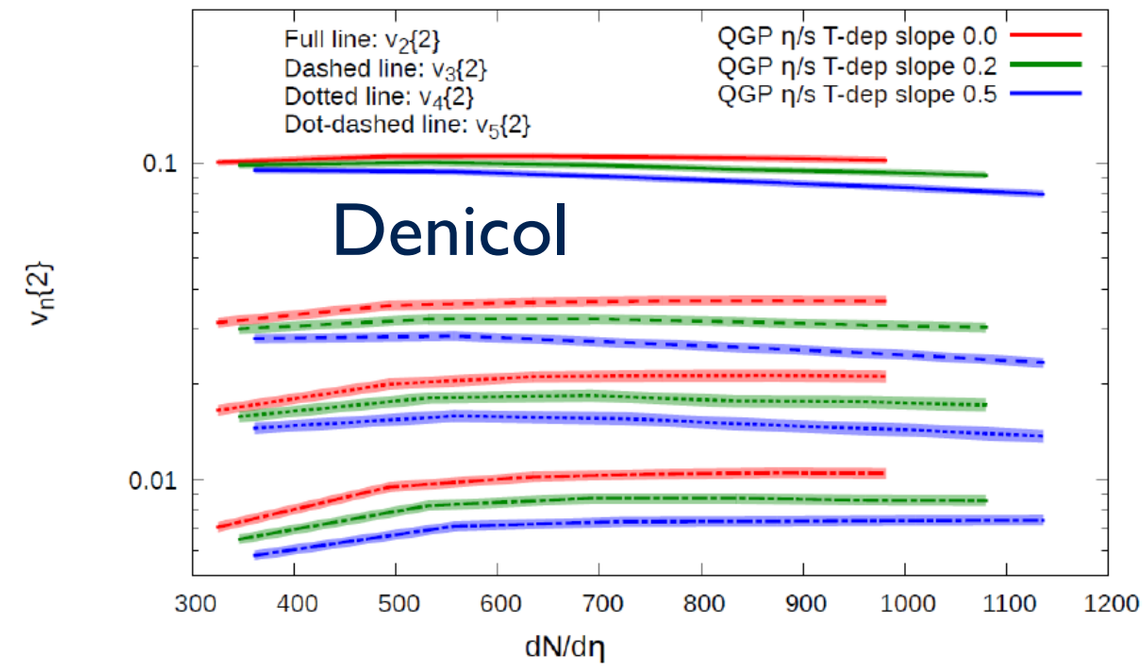


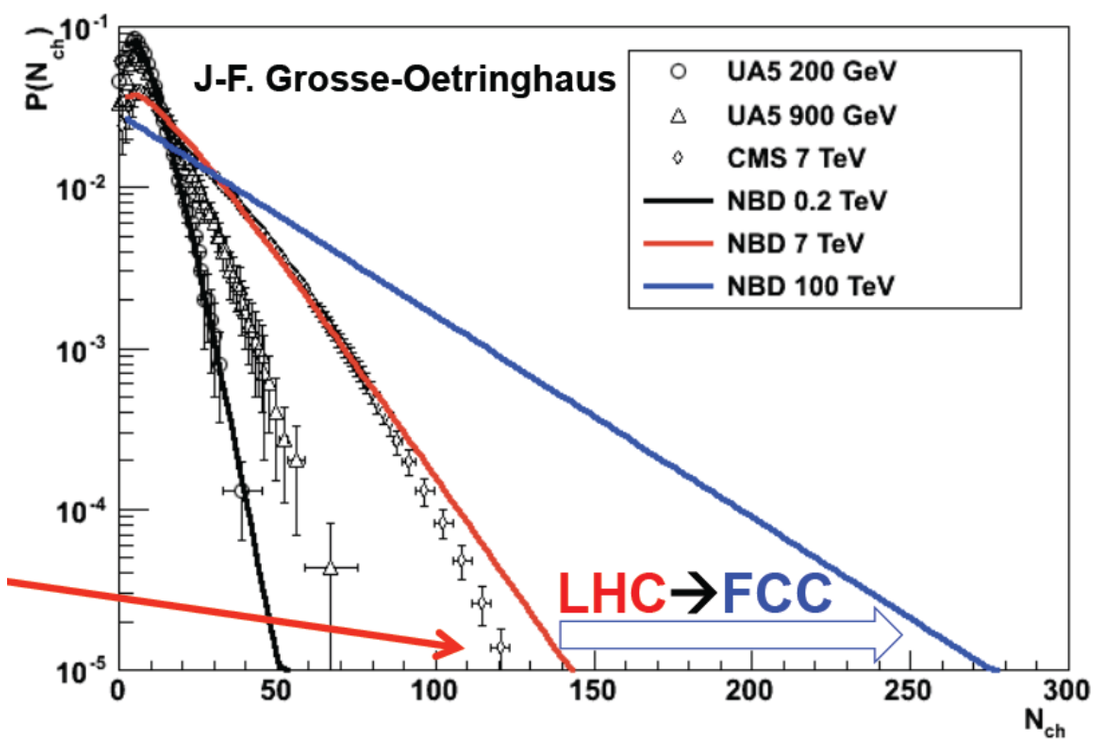
- Large increase: thermal production may overcome shadowing.

Correlations:



- Higher multiplicity may profit collective flow studies e.g. T dependence of η/s.

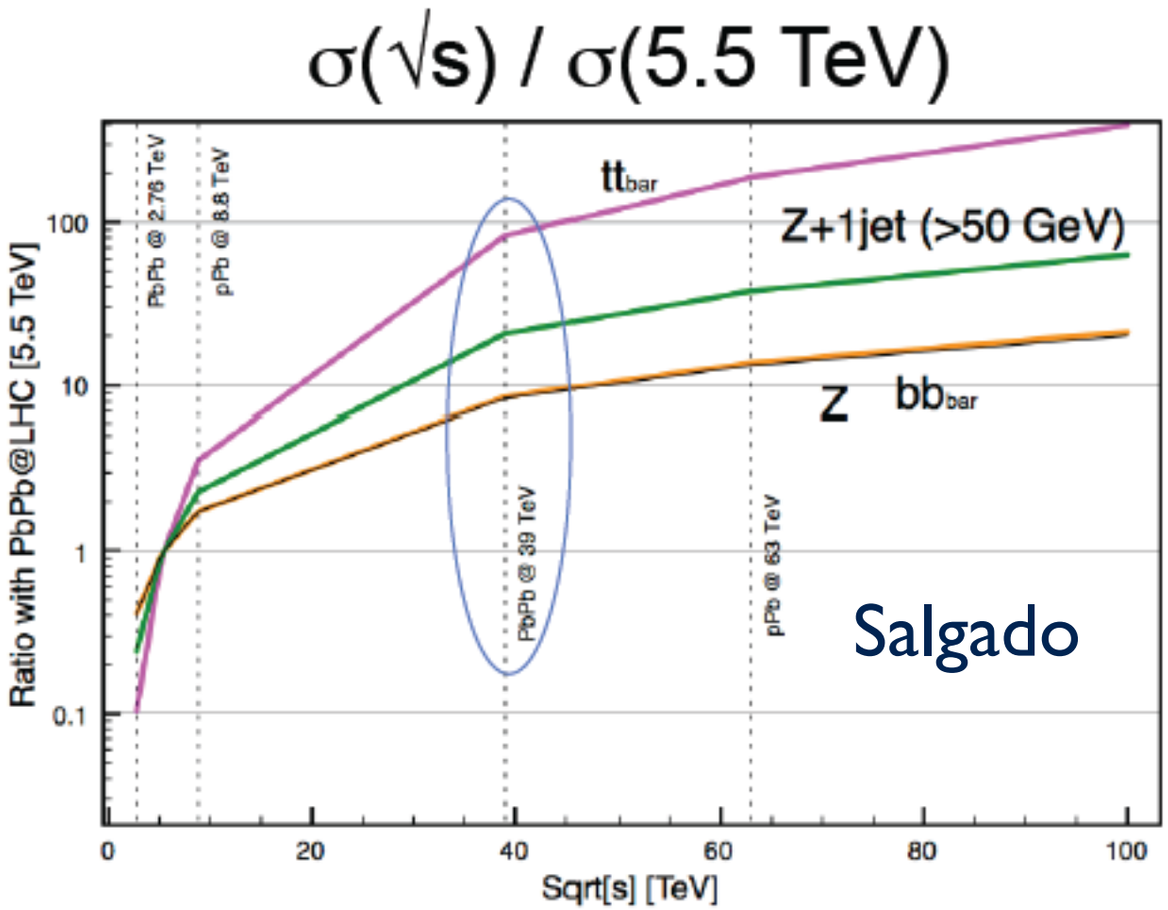


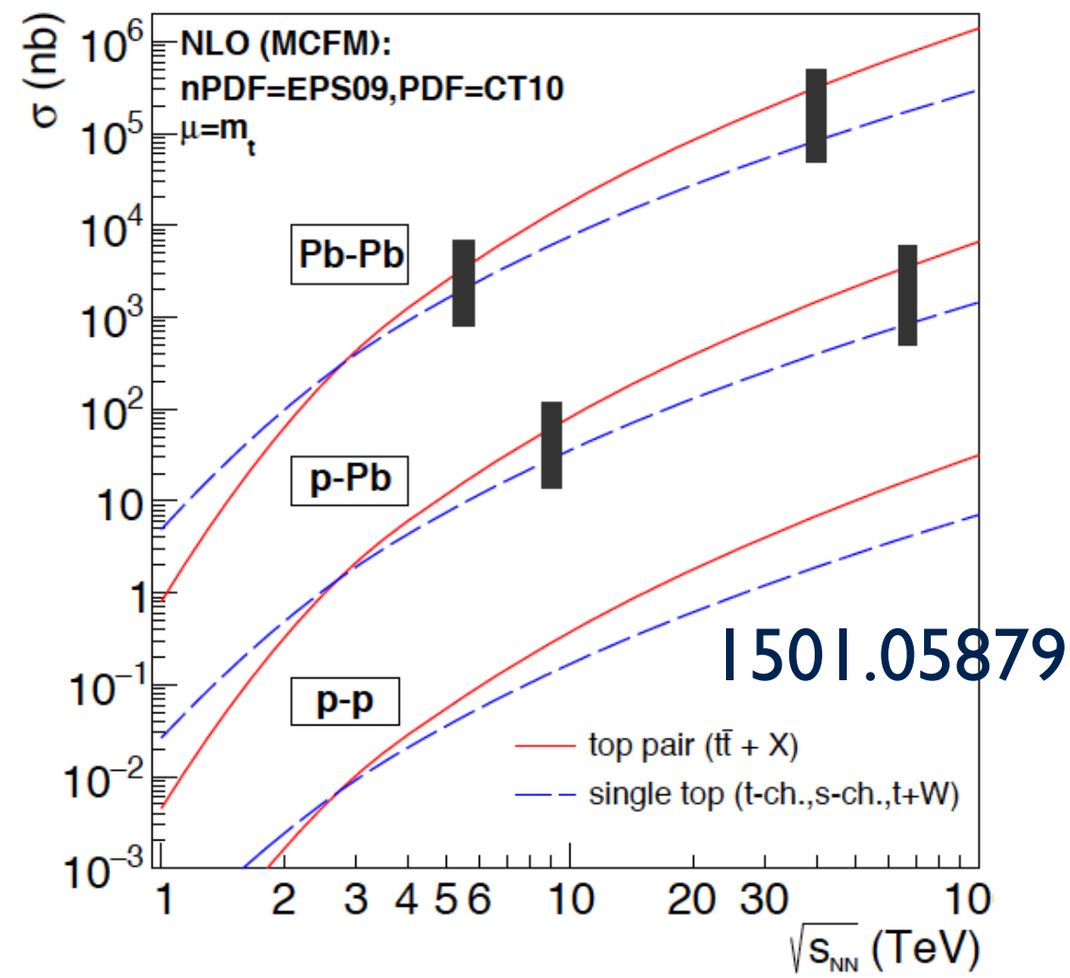


- Much larger multiplicity in pp would help to understand the eventual onset of collectivity in pp and pA: flow-like features, ridge, $\langle p_T \rangle$,…

Hard probes: yields

- Hard probes are much abundantly produced.





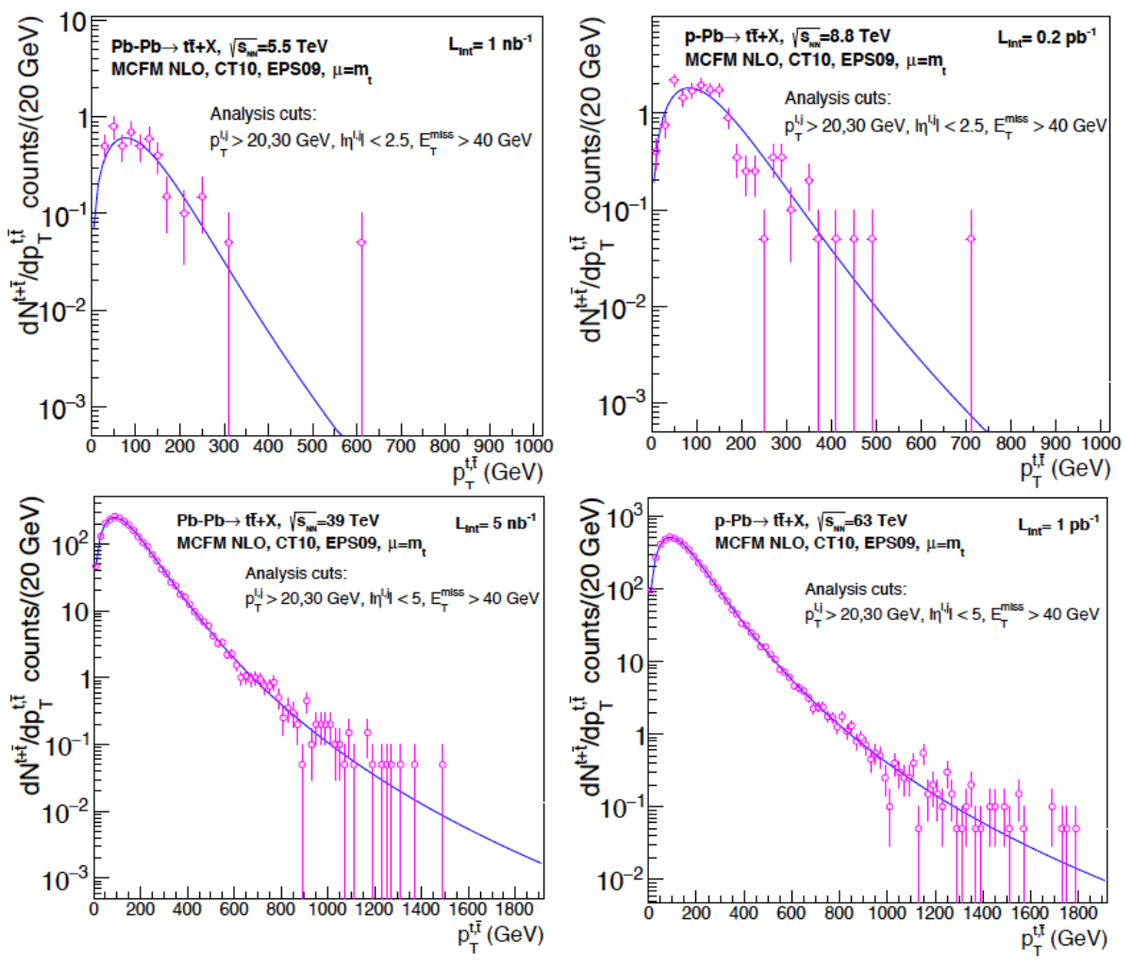
- This could make possible the use of top, abundant EWB+jet events,…
- New temperature and density range may affect hard probes: Υ melting, bbar regeneration,…

Hard probes: nPDFs

- Top could be used to constrain the nuclear glue as done now in pp collisions at the LHC. d'Enterria, Krajczac, Paukkunen, 1501.05879, Hessian reweighting

$\int \mathcal{L}$=10 nb^{-1} (1 pb^{-1}) in PbPb (pPb)

System	$\sqrt{s}$	$\mathcal{L}_{\rm int}$	Number of top+antitop quarks $t\bar{t} \to b\,\bar{b}\,\ell\ell\,\nu\nu$	Number of top+antitop quarks $t\,W \to b\,\ell\ell\,\nu\nu$
Pb-Pb	5.5 TeV	1 nb^{-1}	90	3
p-Pb	8.8 TeV	0.2 pb^{-1}	300	10
Pb-Pb	39. TeV	5 nb^{-1}	47 000	1 300
p-Pb	63. TeV	1 pb^{-1}	100 000	2 600



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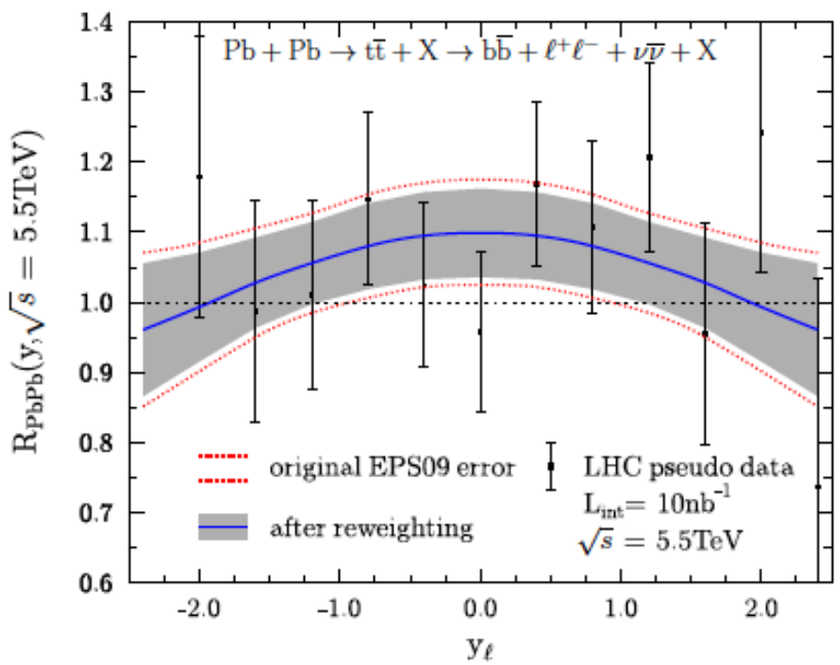

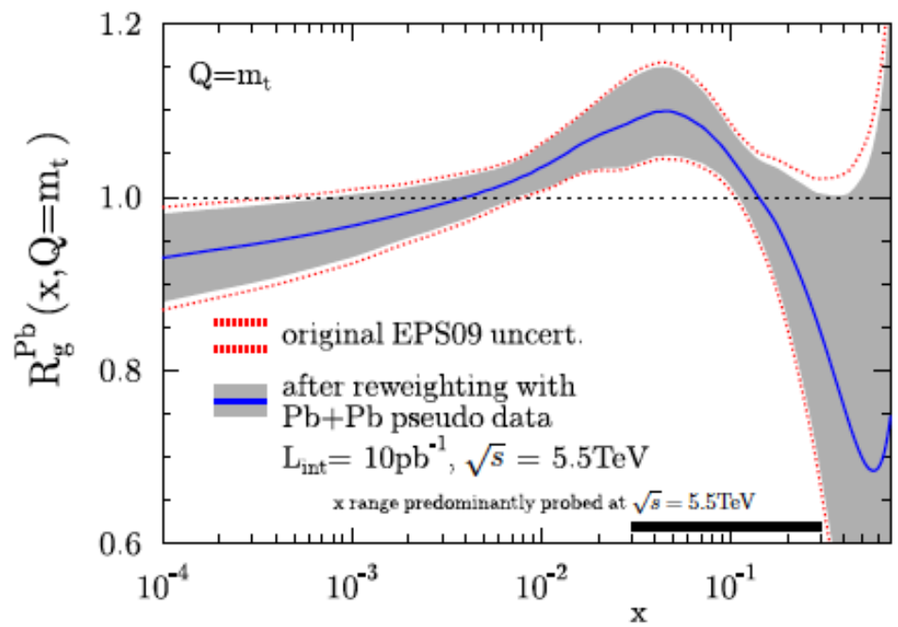

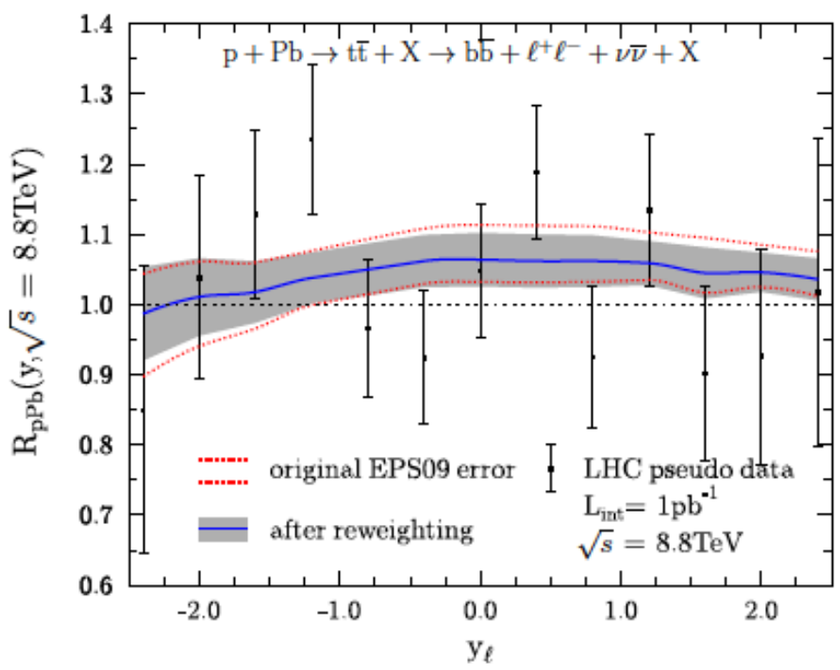

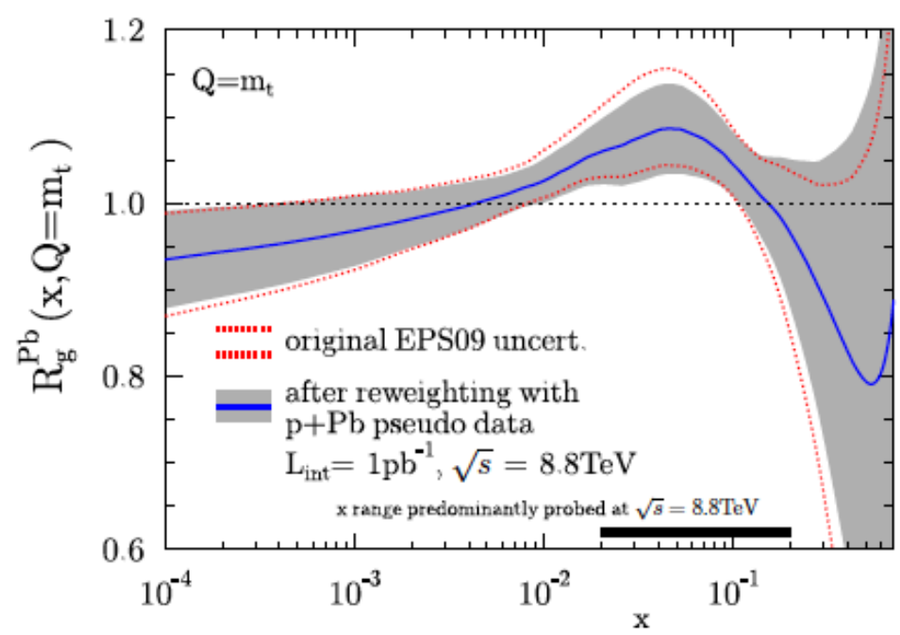

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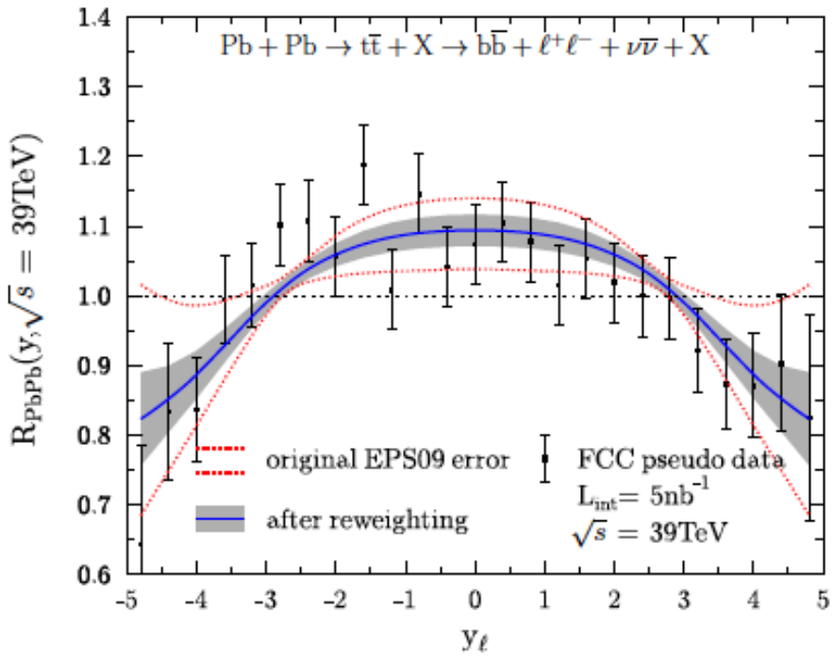

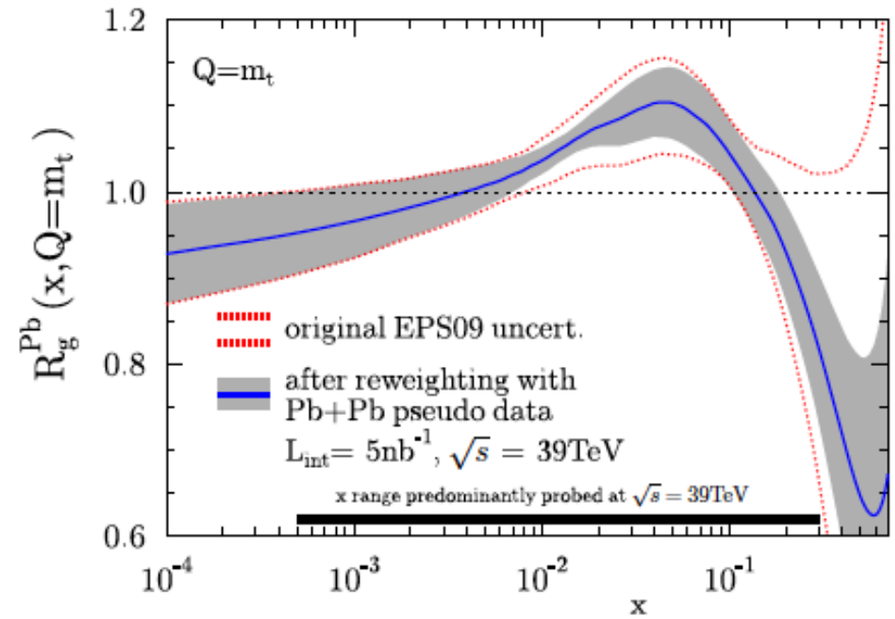

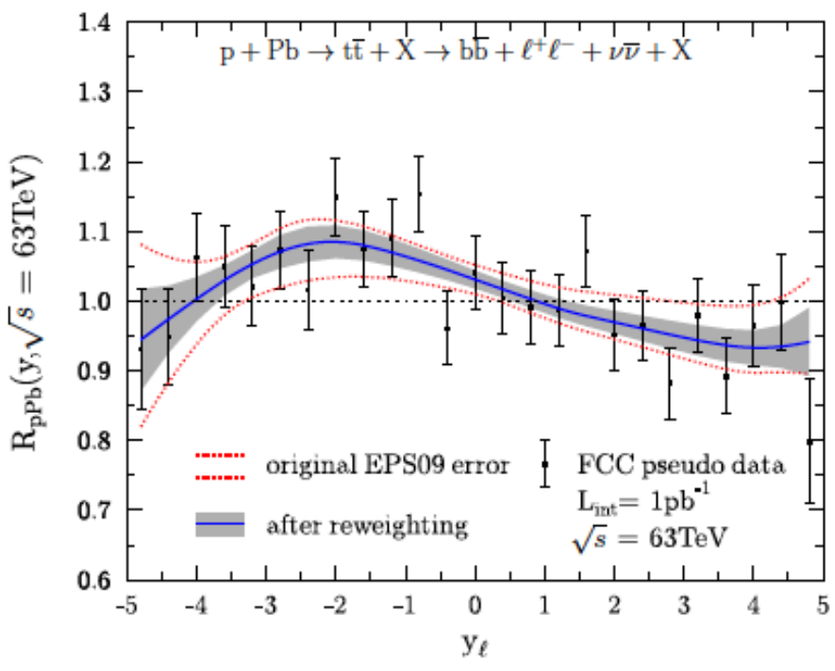

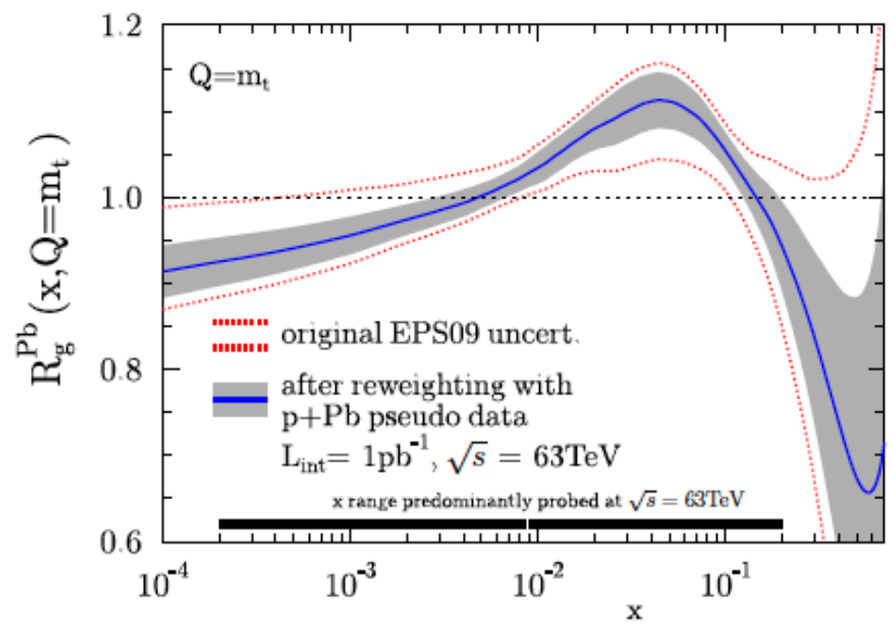

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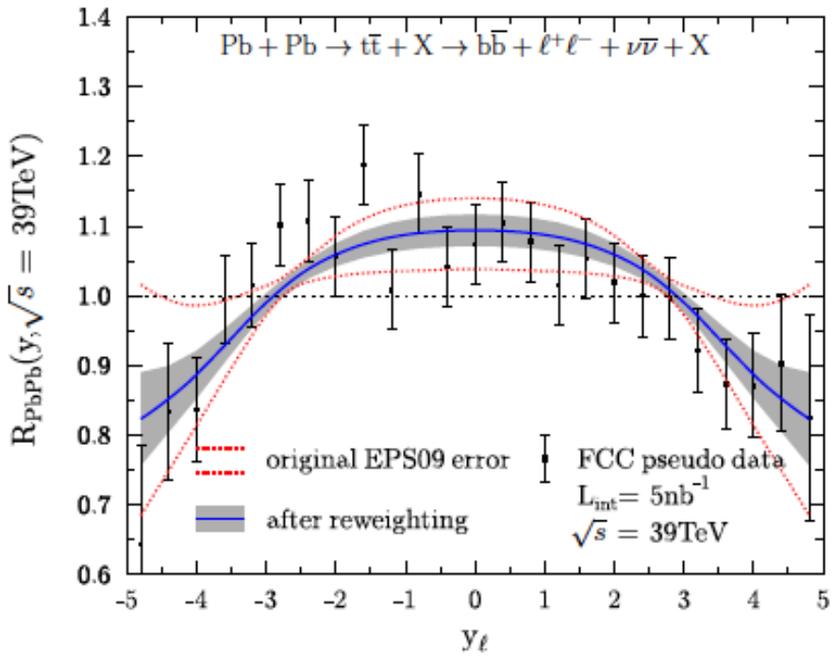

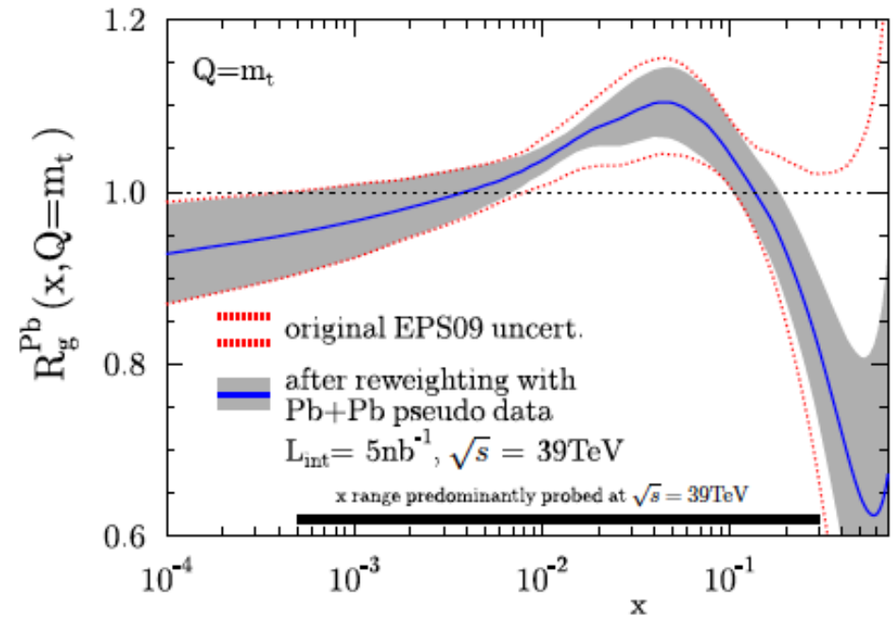

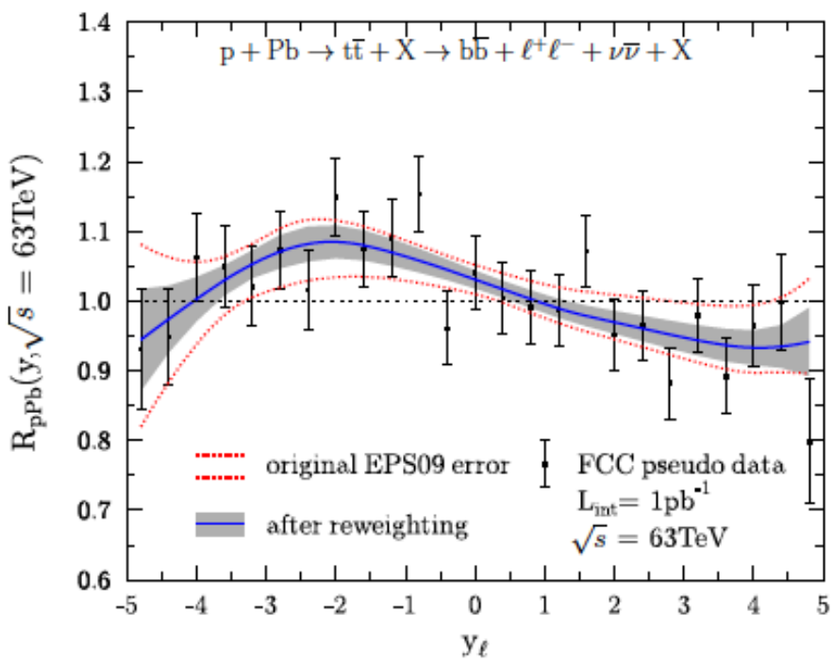

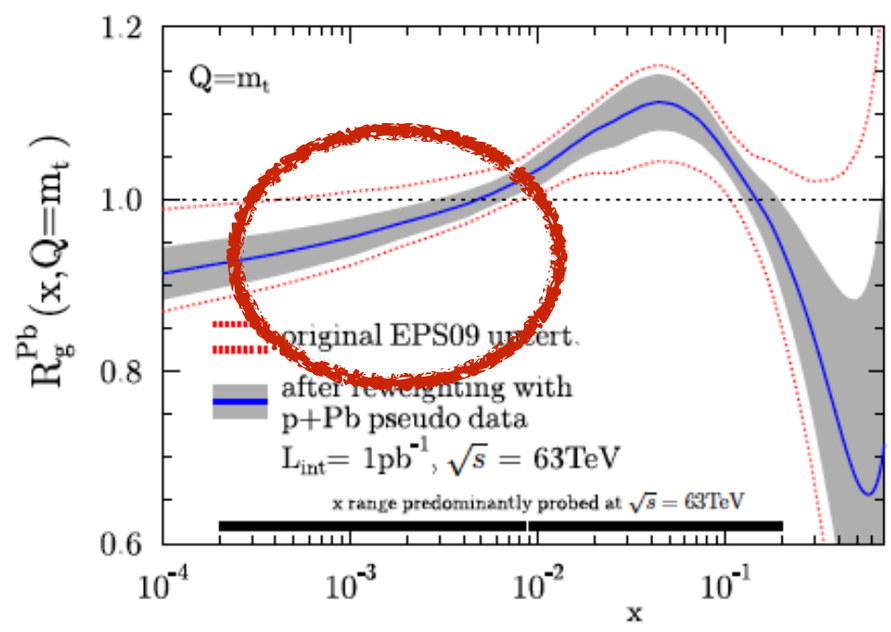

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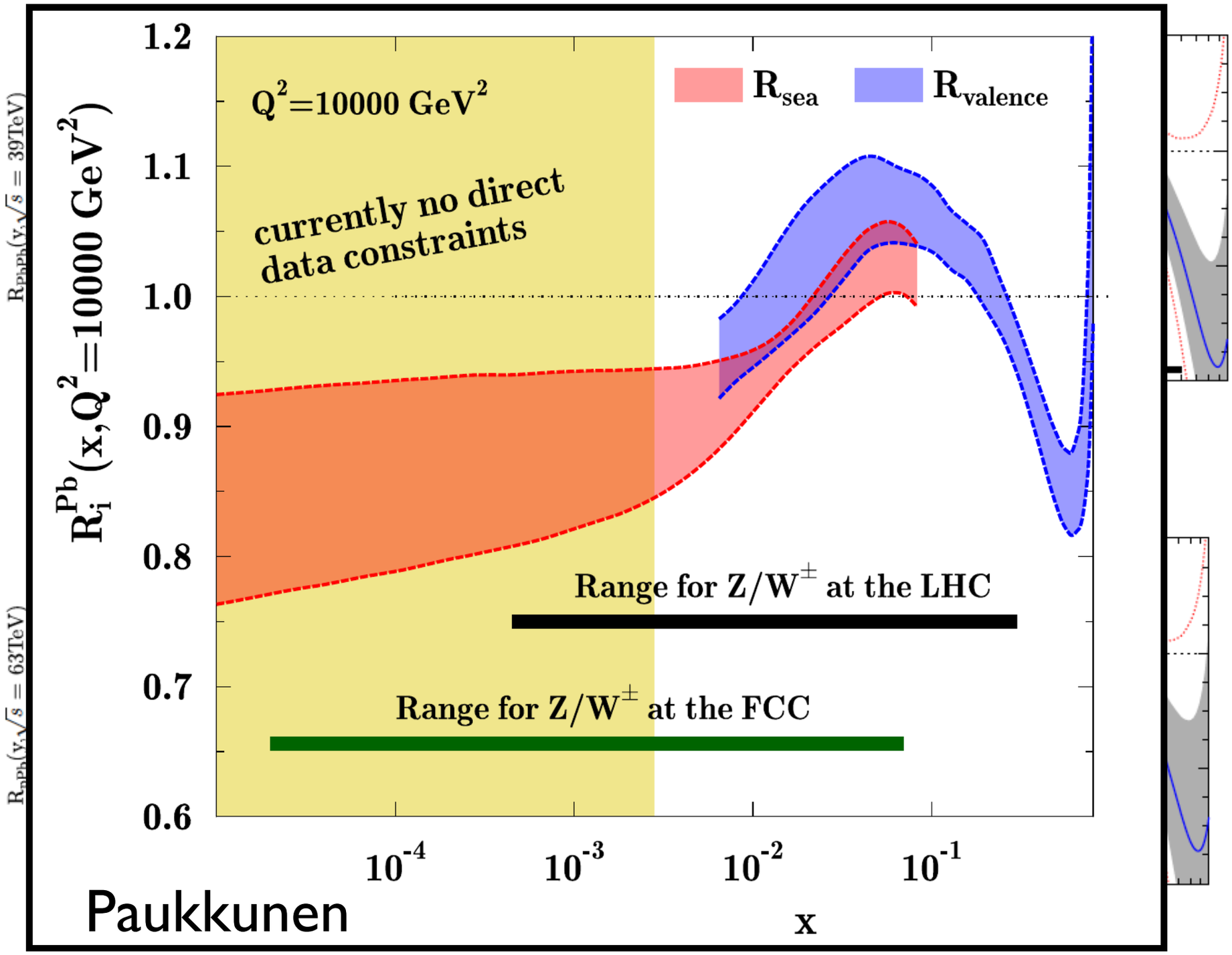
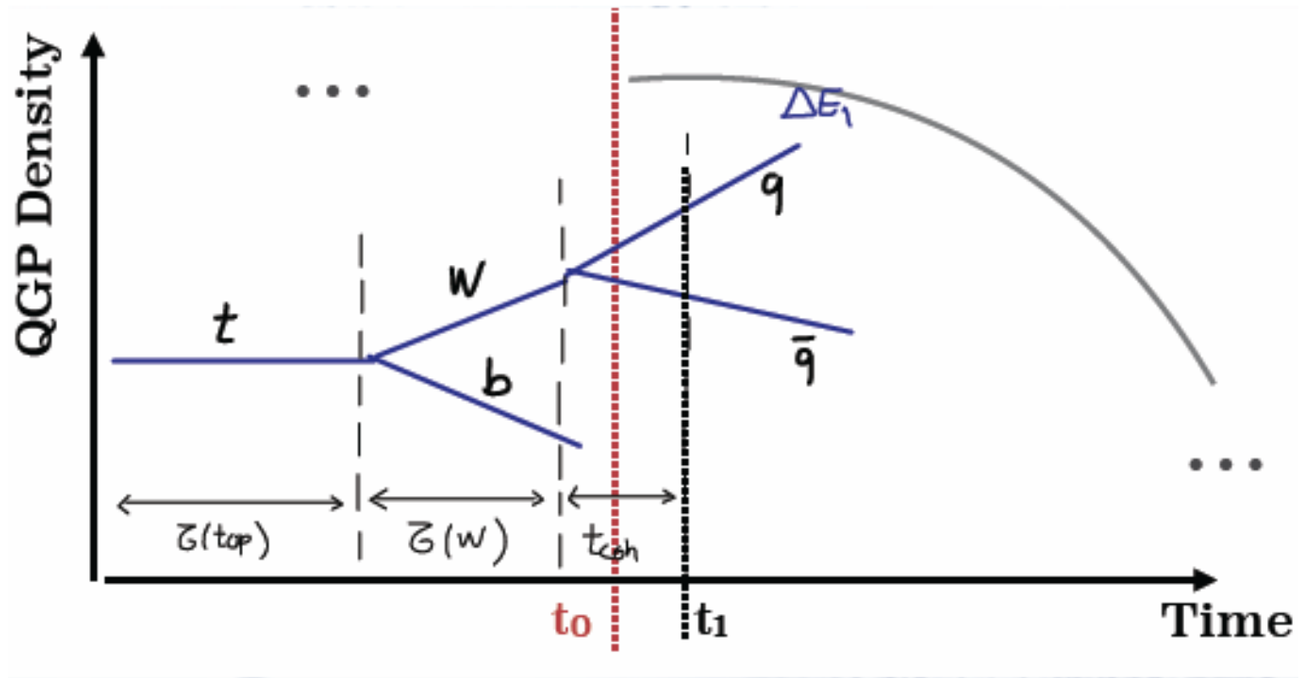


Hard probes: boosted tops

- Use boosted tops to probe the time scales in the medium and the energy loss mechanism.

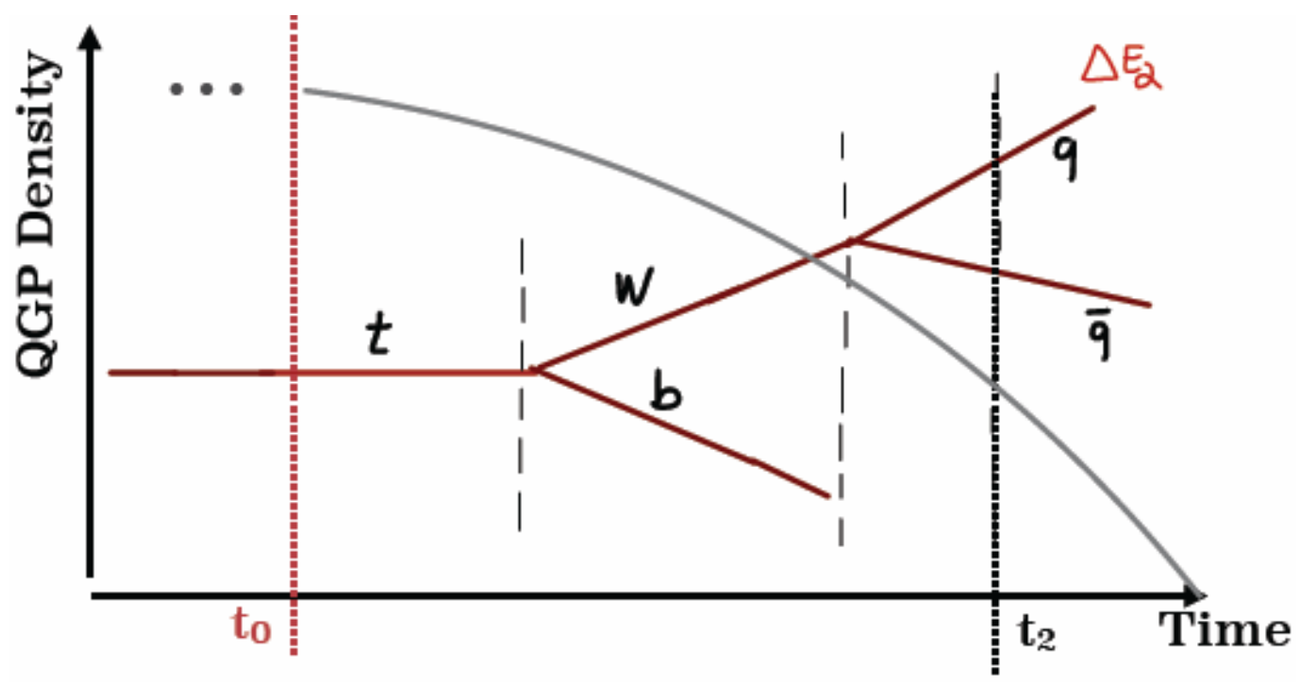
$$b\bar{b} + \ell + 2\,jets + \not{E}_T$$

yields 5 times those of the previous channel



Apolinario at ECT*, $t_{coh} \sim 1$ fm/c for $P_T^{top} \sim 800$ GeV.

increasing p_T^{top}



$\Delta E_2 < \Delta E_1$

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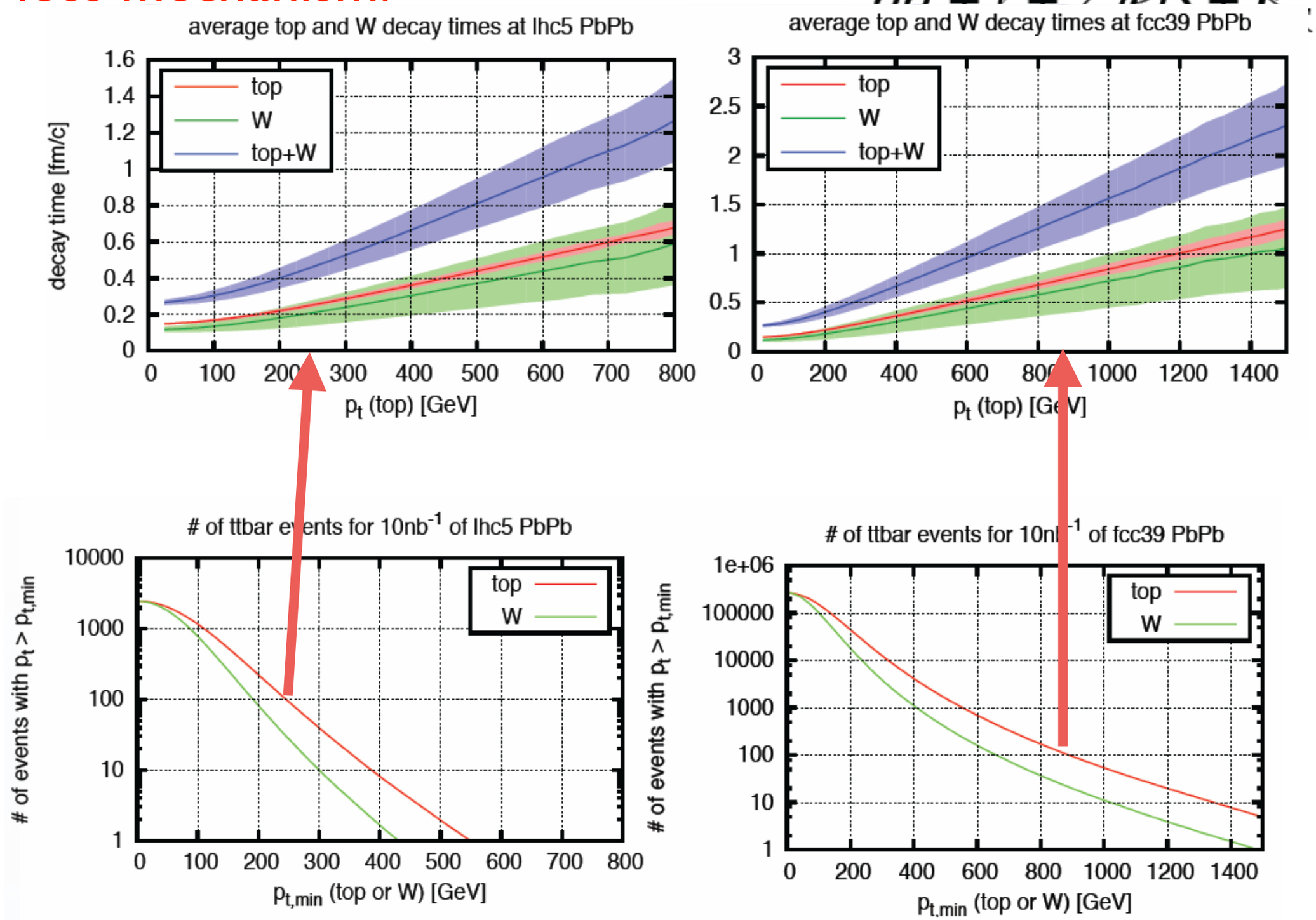
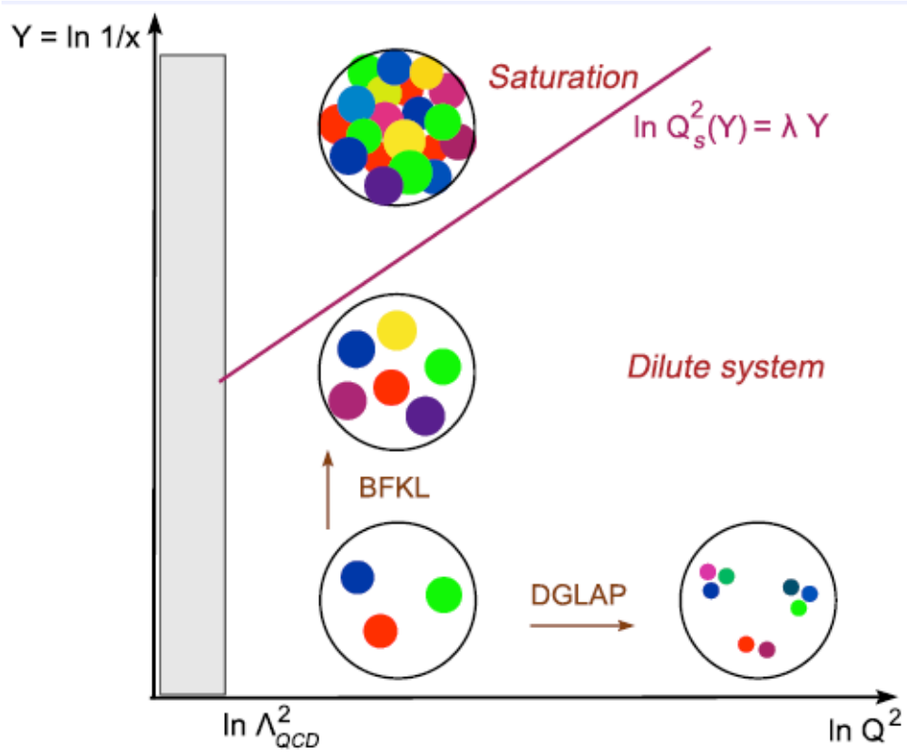
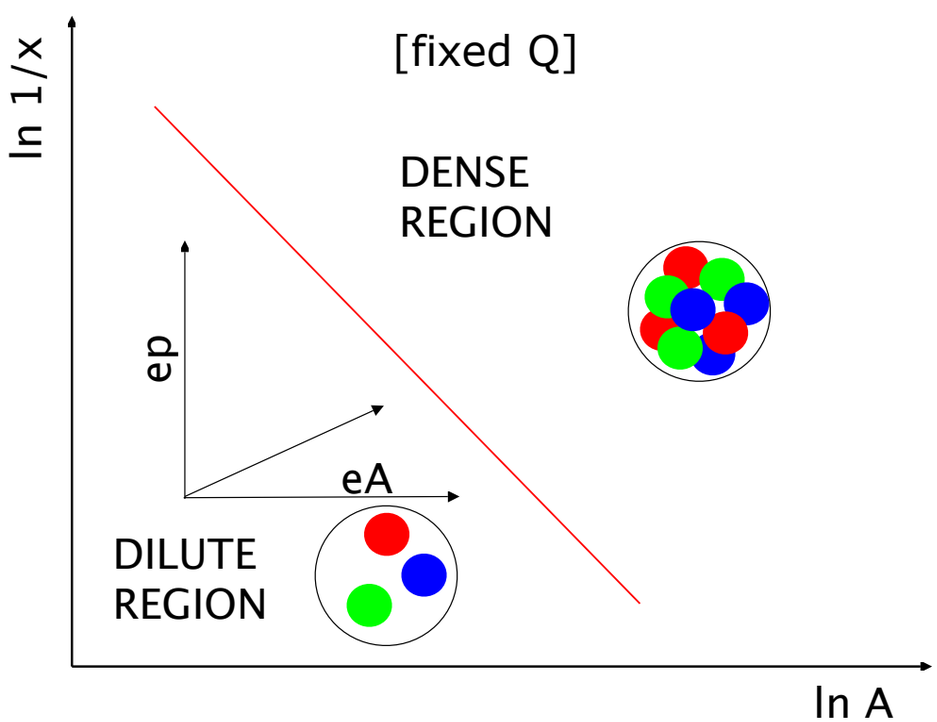


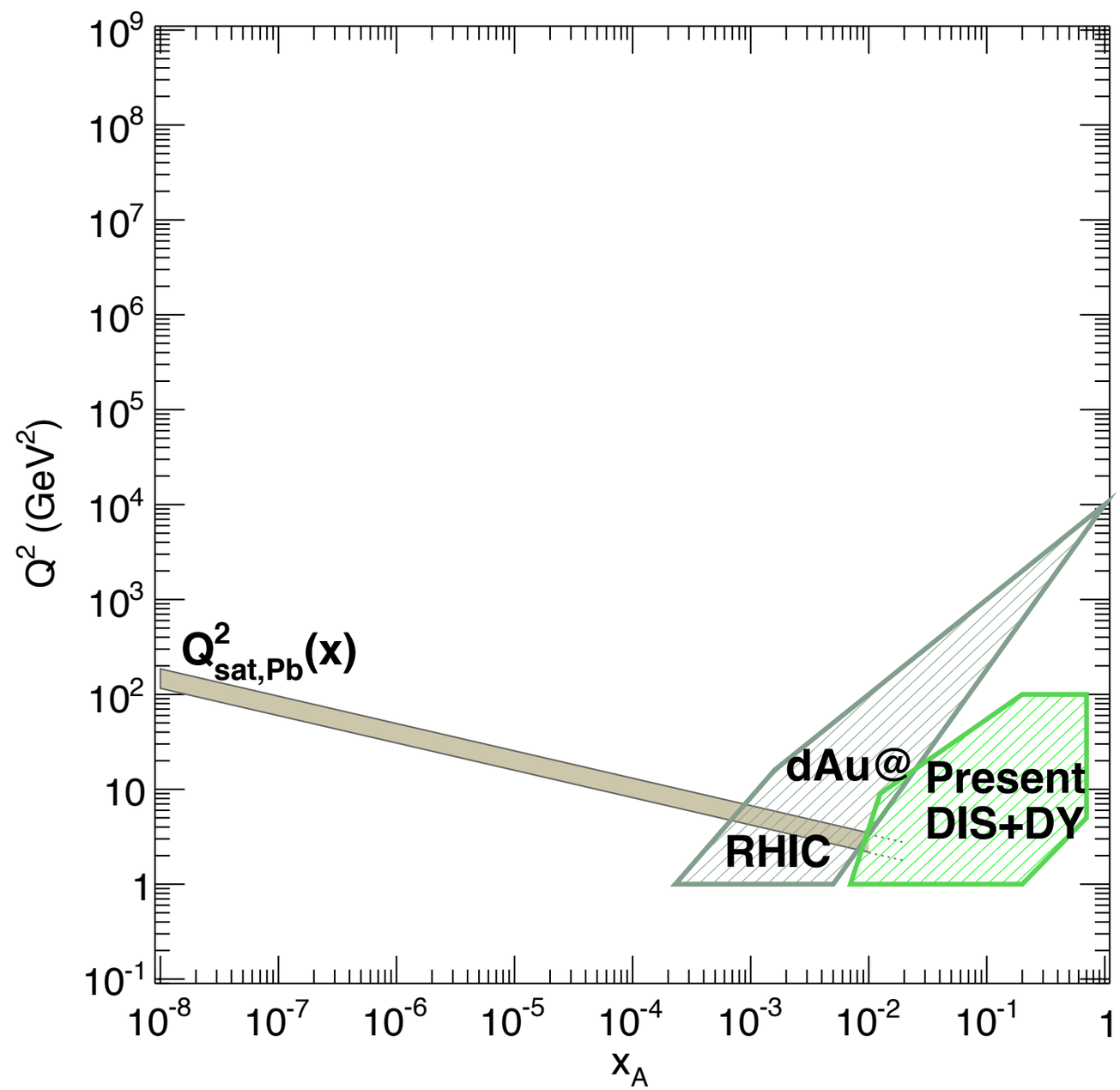
Small x (I):

- Test whether (perturbative) saturation lies in the accessible kinematic region, and understand how it works.



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$





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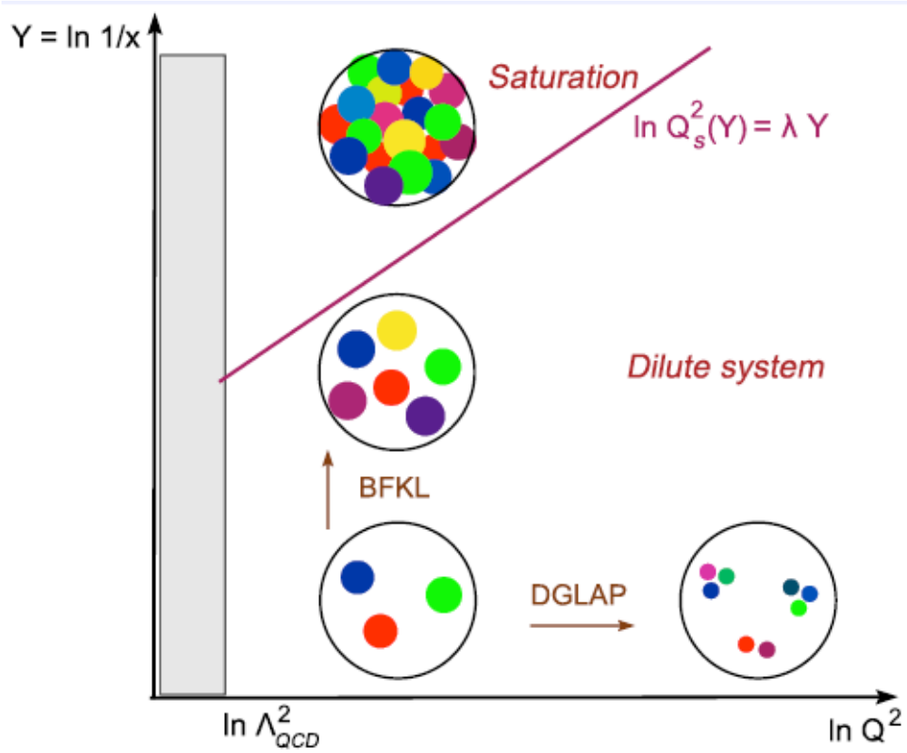

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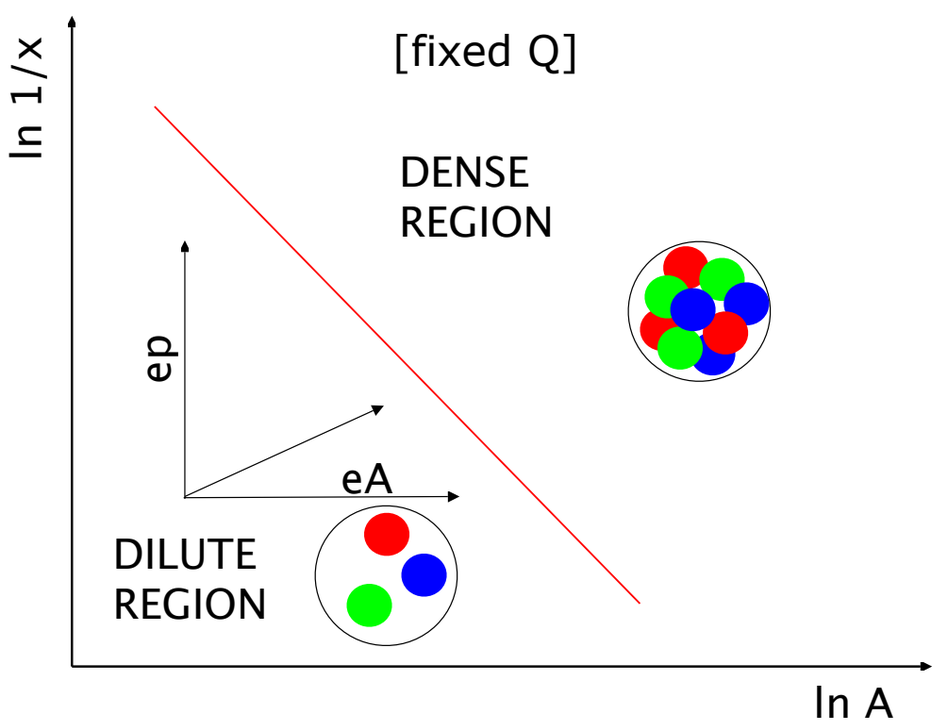

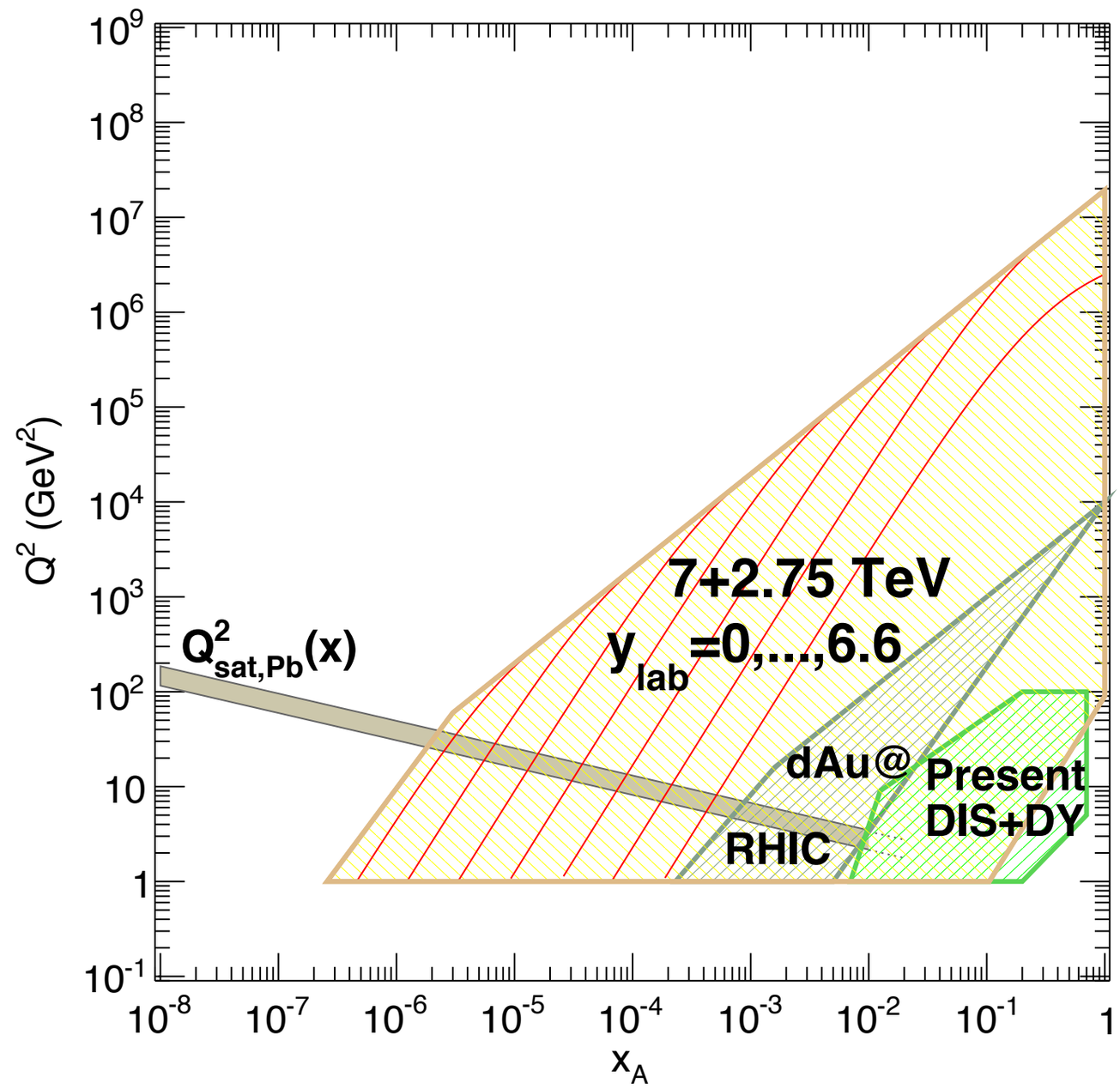

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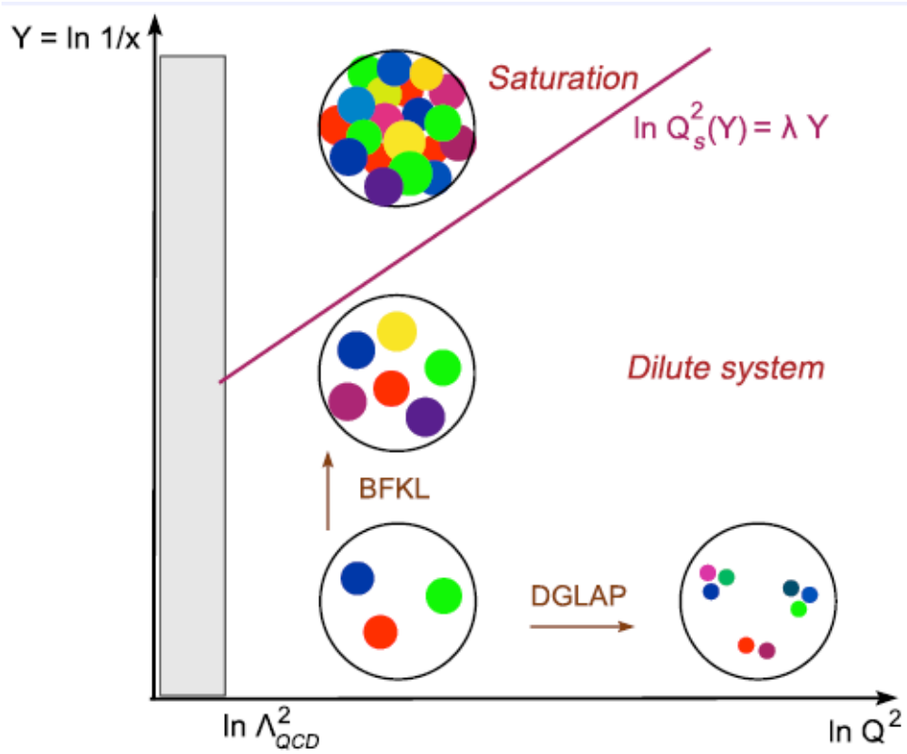

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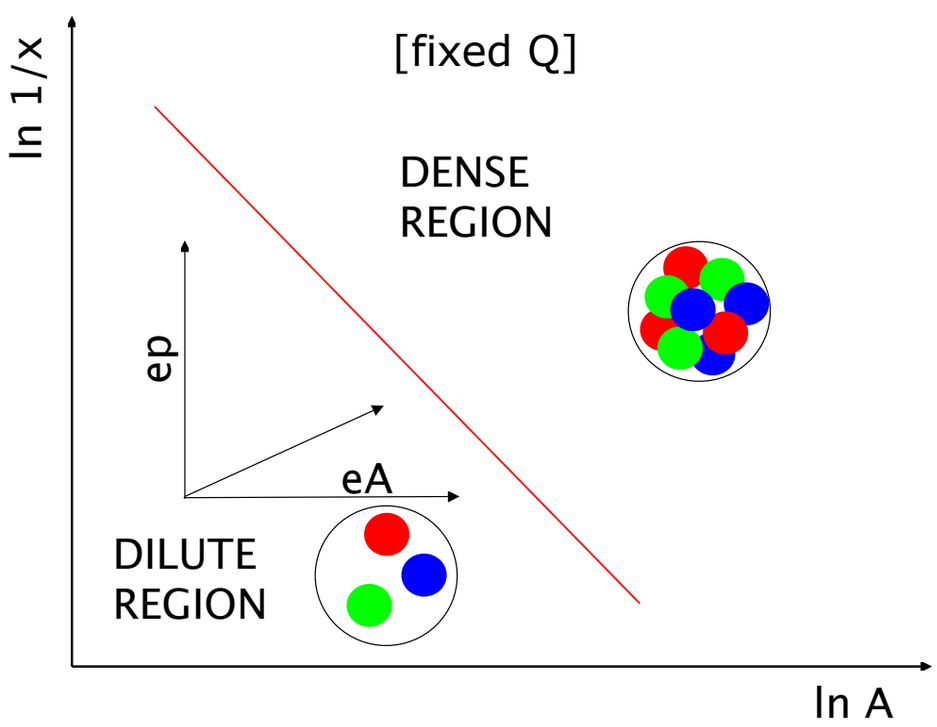

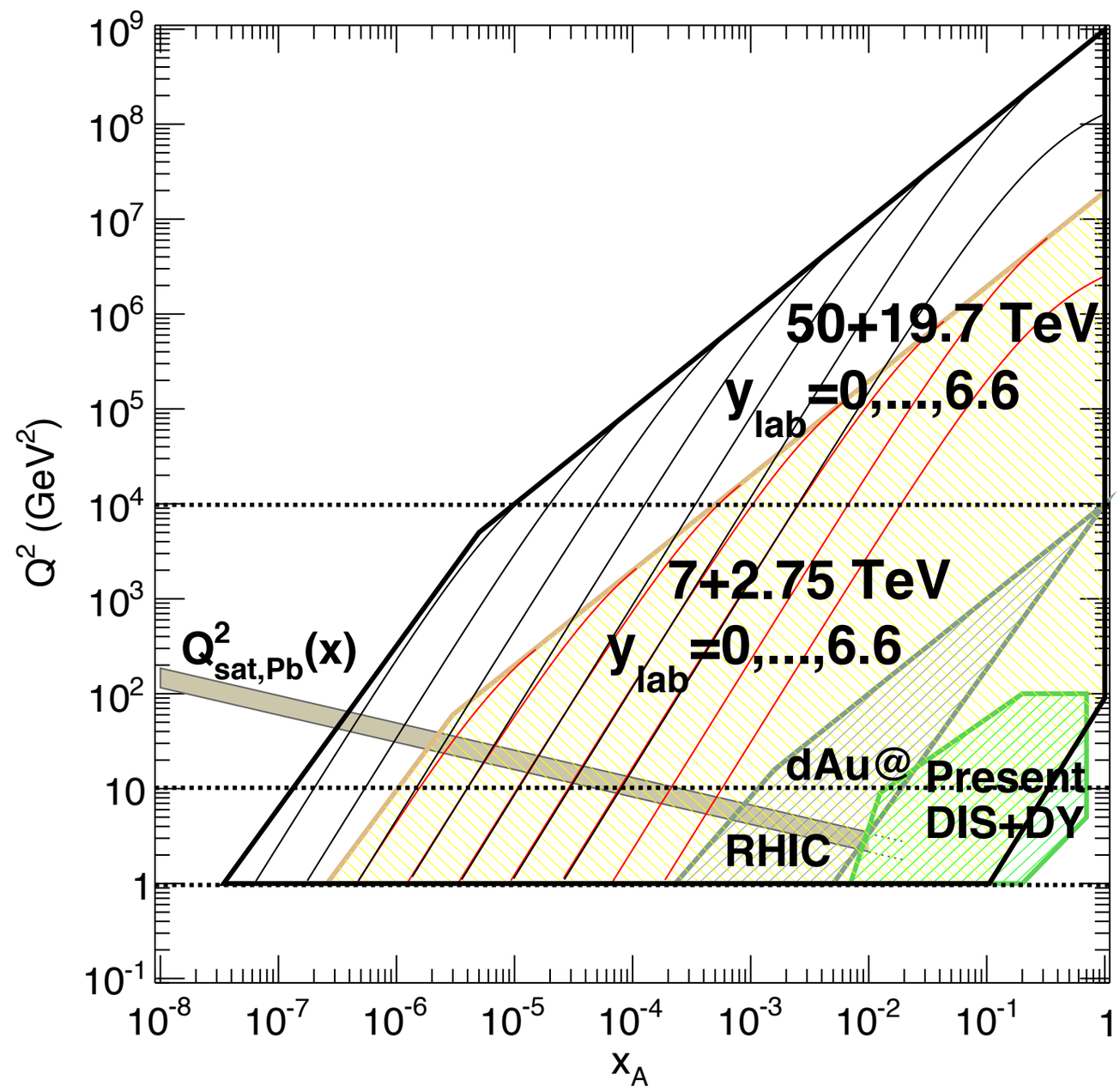

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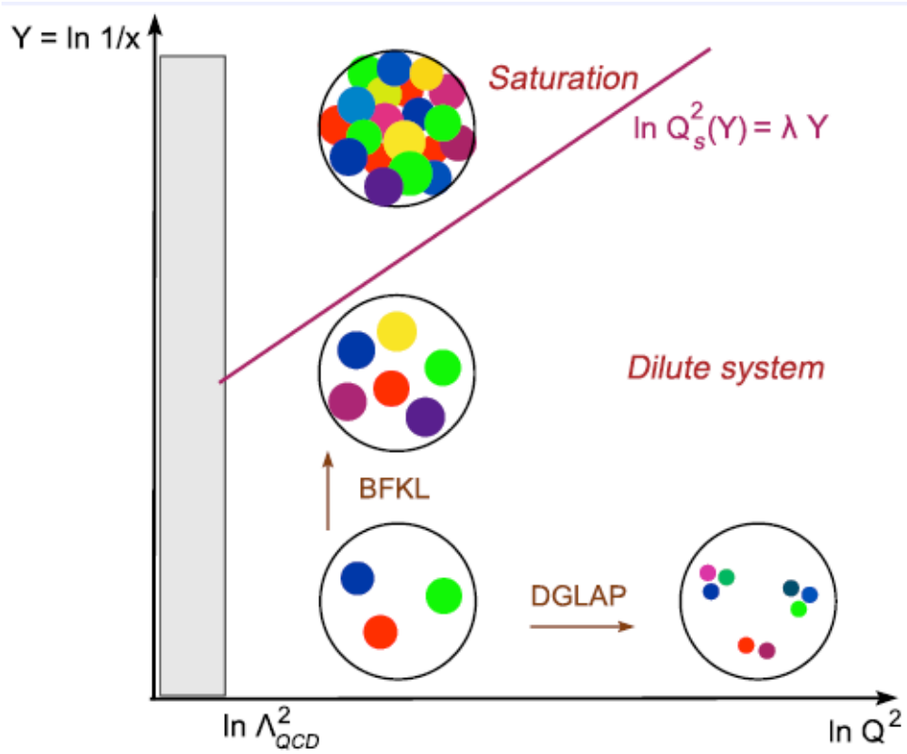

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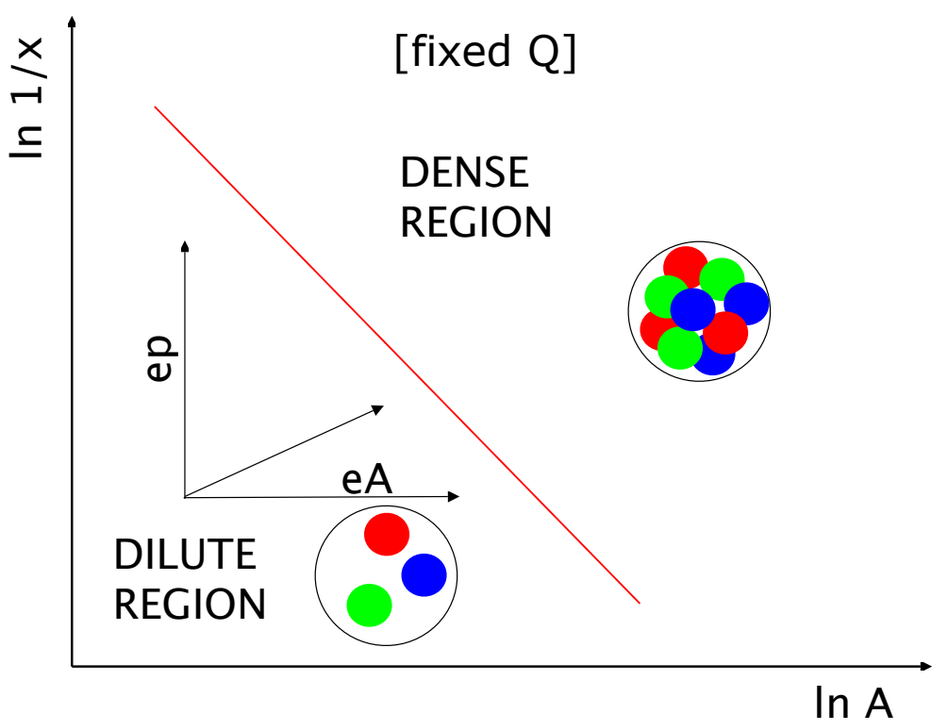

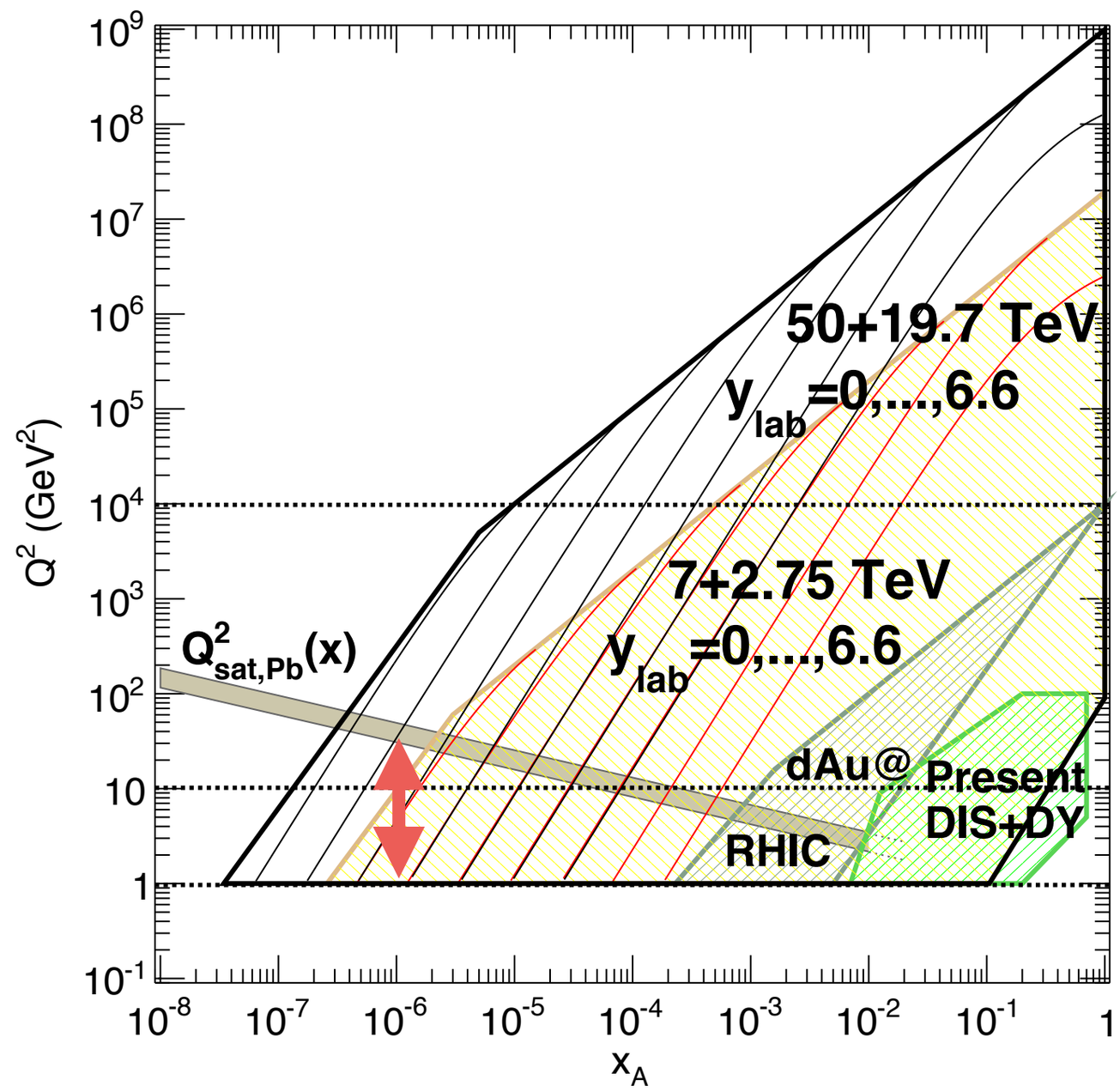

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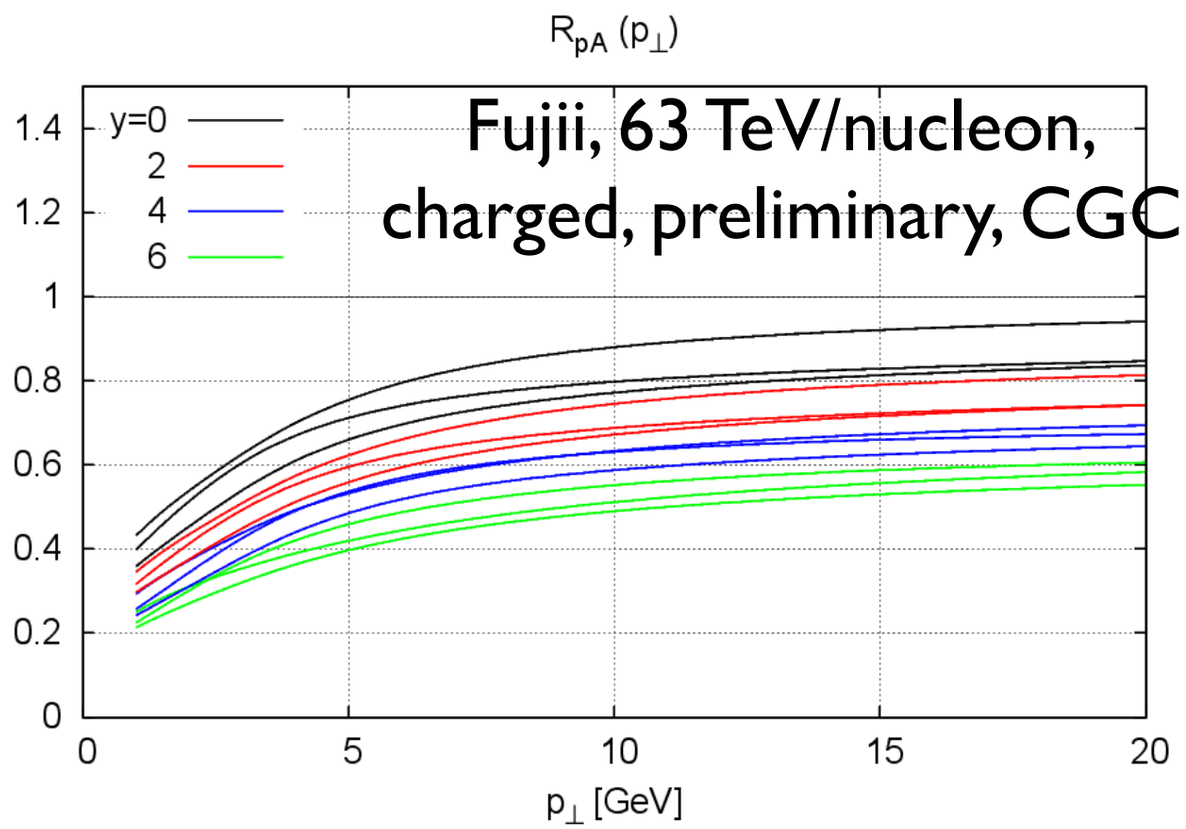

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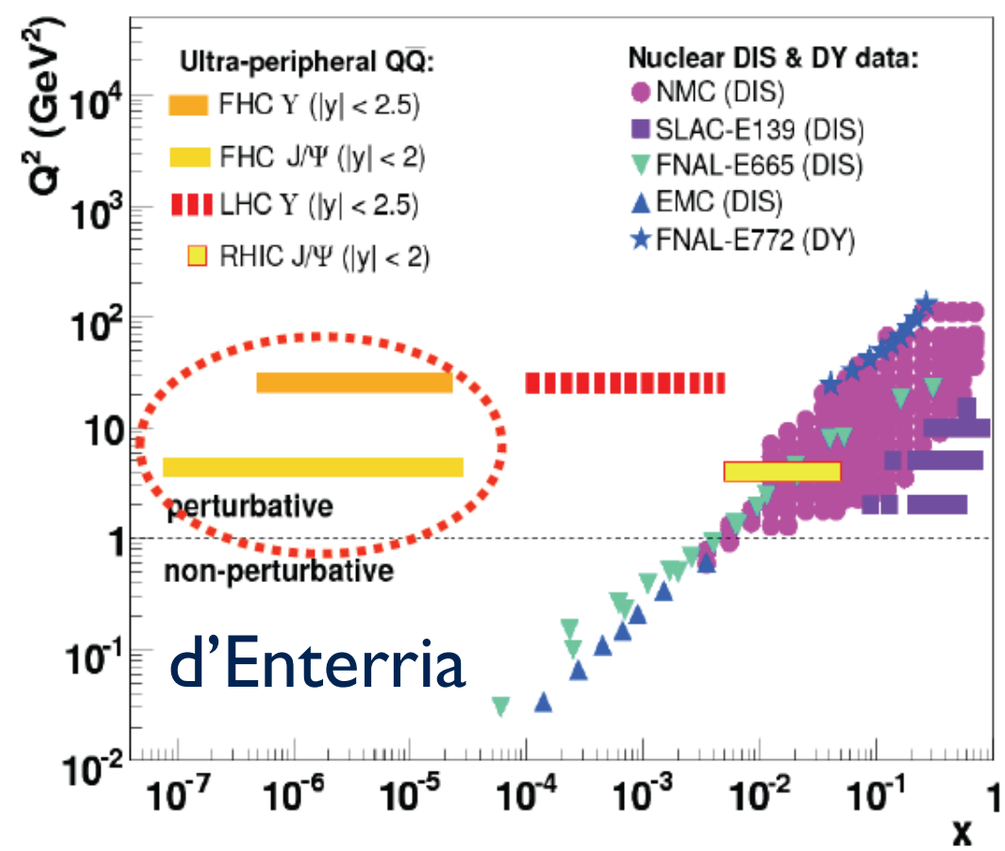

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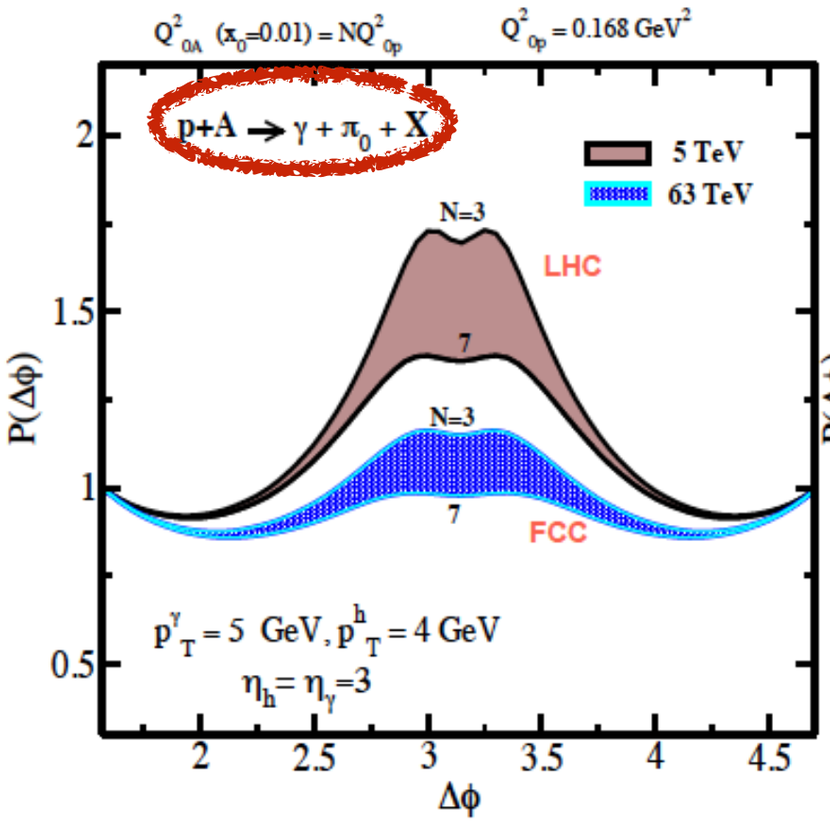

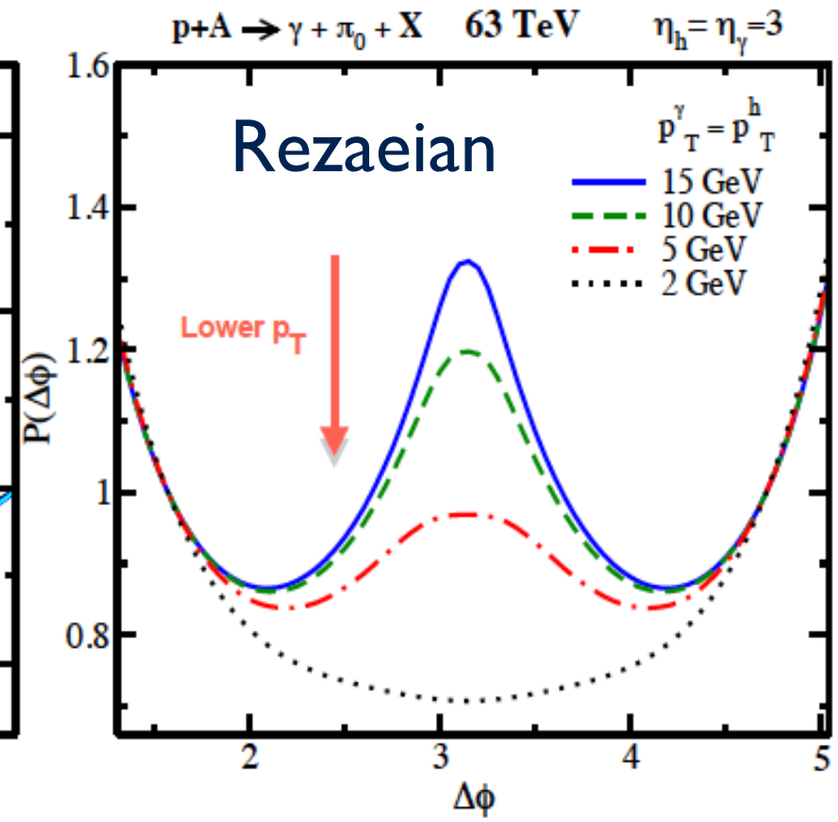

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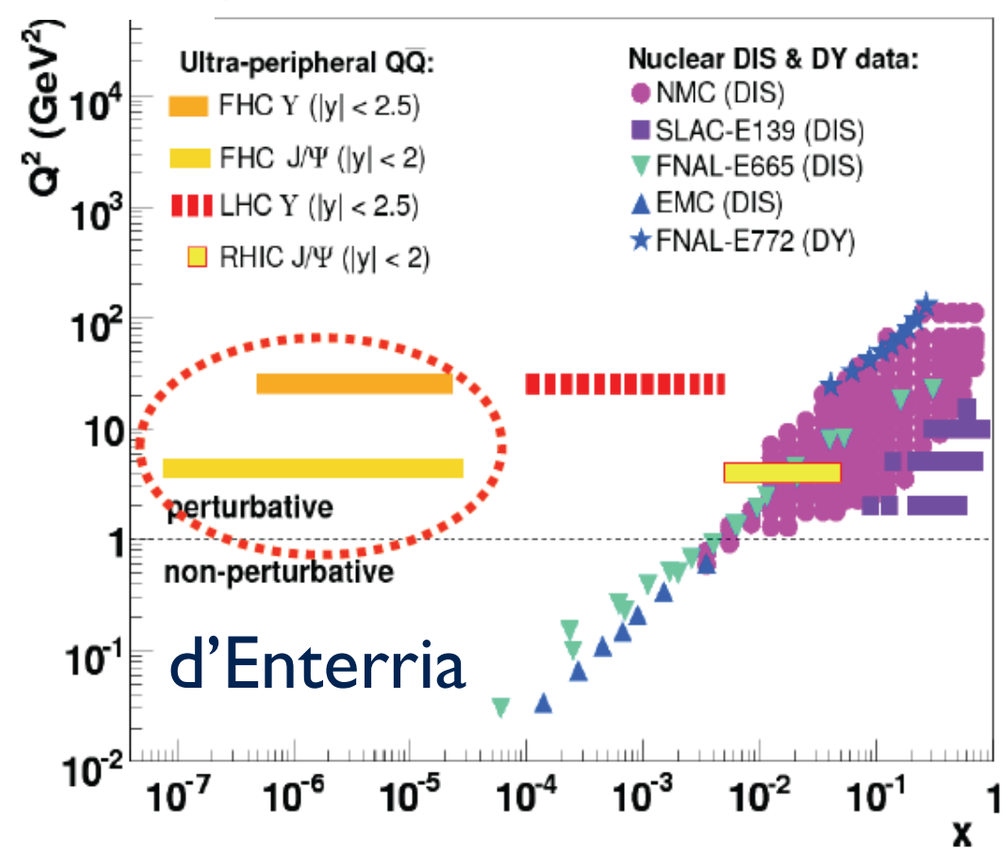

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  - ➜ Hotter, longer-lived medium with larger opportunities to observe collectivity from small to large systems.
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  - ➜ Access to a large perturbative domain at small x: saturation.
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- **Outlook:**
  - ➜ CDR for the next European Strategy for Particle Physics in 2017/2018.
  - ➜ Organisation: collaboration established, with FCC-hh, FCC-ee and FCC-he groups.
  - ➜ Initial physics document to be produced for next spring.
  - ➜ FCC-AA coordinators: A. Dainese, S. Masciocchi, C. A. Salgado, U. A. Wiedemann.
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Visit the web pages: everybody is more than welcome to join!!!

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- **Su**

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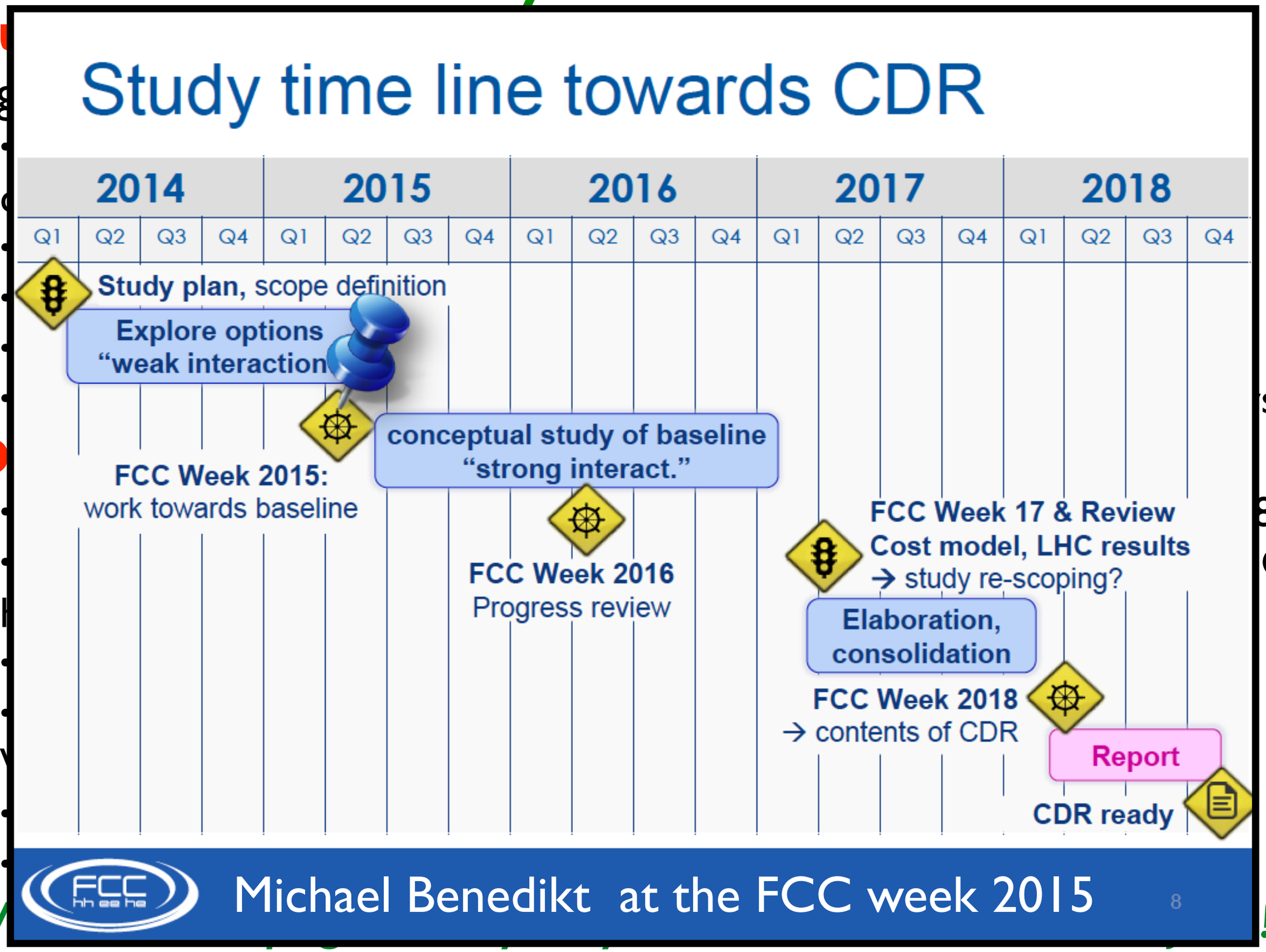

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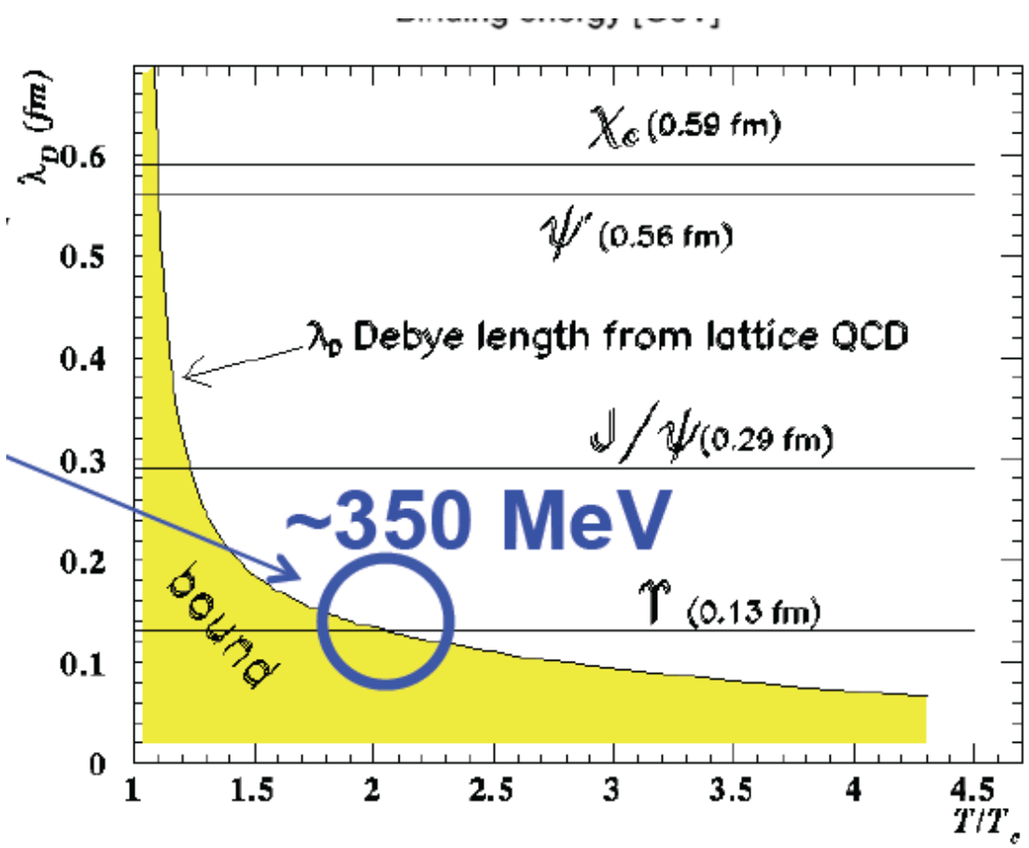
Backup:

Hard probes: quarkonium



- Υ may melt at the FCC: pushing the thermometer to higher values.

- Recombination, enhanced by thermal charm production, will play a dominant role for ccbar states: R_{AA}, v_2, D/τ bbbar states?