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CONSIDERAZIONI SU ALTRE LINEE  
DI RICERCA INFN / FIS. TEOR.

# PROLOGO

Non sono un habituè di questo tipo di seminari, e quindi ho chiesto cosa ci si aspettasse

“Se tu avessi un gruppo di 20 giovani, su quali linee di ricerca e problemi li indirizzeresti? — parla di questo.”

Compito difficile anche perchè la scelta del campo è talvolta più importante (per la carriera) della capacità di dare soluzioni.

# TRE RISPOSTE FACILI\*

1. Onde gravitazionali, multi-messenger etc.
2. Computazione / informazione quantistica
3. Intelligenza artificiale / "Machine Learning"

\* quelle che più ci si vuole sentir dare

# TRE RISPOSTE FACILI

## 1. Onde gravitazionali, multi-messenger etc.

Grande prova della fisica sperimentale e della tecnologia più raffinata, dalla costruzione di apparati alla analisi dei dati.

Come tanti, sto cercando di capire, da quello che sento, quali siano i "deliverables" nella fisica teorica in questo campo, al di là dei lavori fondamentali del passato, che esauriscono rapidamente quello che un non-esperto direbbe che c'è da fare.

Stelle di bosoni /assioni? Fisica nucleare, equazioni di stato etc? ...

# TRE RISPOSTE FACILI

## 2. Computazione / informazione quantistica

La grande promessa del futuro. In termini di "deliverables" si presenta come il campo che "nell'arco dei prossimi dieci anni porterà a progressi sorprendenti, e finalmente al QC "

La domanda che trovo più affascinante è "ammesso che qualcuno ti metta in mano un QC funzionante, quale problema risolvi?". C'è una intera comunità al lavoro su questo campo, specie in MS Q-Labs, e Google.

# TRE RISPOSTE FACILI

## 3. Intelligenza artificiale / "Machine Learning"

"Non si sa come mai certi algoritmi di deep learning funzionino così bene" — un problema estremamente interessante. Non penso che sia così scontato che sarà risolto da fisici, visto che è presente a una comunità vastissima.

Che cosa è la "scienza della intelligenza artificiale?"

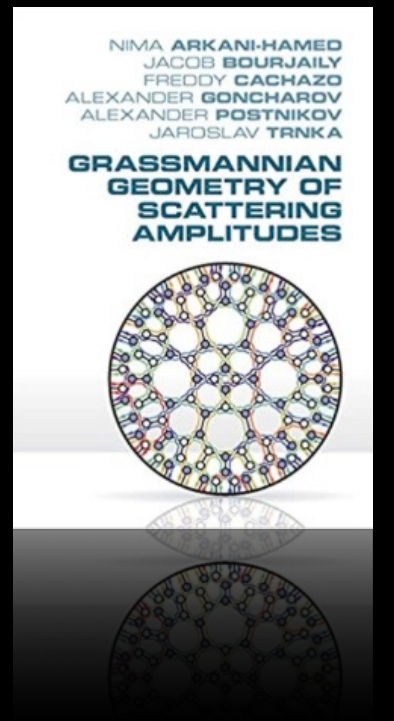
# TRE RISPOSTE DIFFICILI

1. Problemi di base nella teoria quantistica dei campi e delle stringhe.

i) Amplituderon\* ii) AdS/CFT iii) Estensioni BSM

2. Materia oscura, Neutrini (Dirac o Majorana?!), Raggi cosmici.

3. Risolvere i problemi che la fisica presenta: quelli che ti mette sul foglio e ti da un certo tempo per rispondere. Spesso i problemi che arrivano non sono quelli che si è deciso di voler risolvere e si gira la testa. Grave rischio di metodo.



Ancora oggi resta imbattuto il record di velocità sul tree-level di **Alpha** (F. Caravaglios & M. Moretti).  
(Tentativo a NLO: Moretti, Piccinini, ADP, (e-Print: [0802.4171](https://arxiv.org/abs/0802.4171) [hep-ph])

# INDIRIZZI FUTURI



A guardare troppo la sfera di cristallo si finisce per contemplare la propria immagine.



# ALTRE FACEZIE

Un fisico teorico molto considerato\* ritiene che nella categoria ci siano due figure " quelli che fanno fisica con la **tunica** e quelli che la fanno con la **tuta** ", collocandosi nella prima.

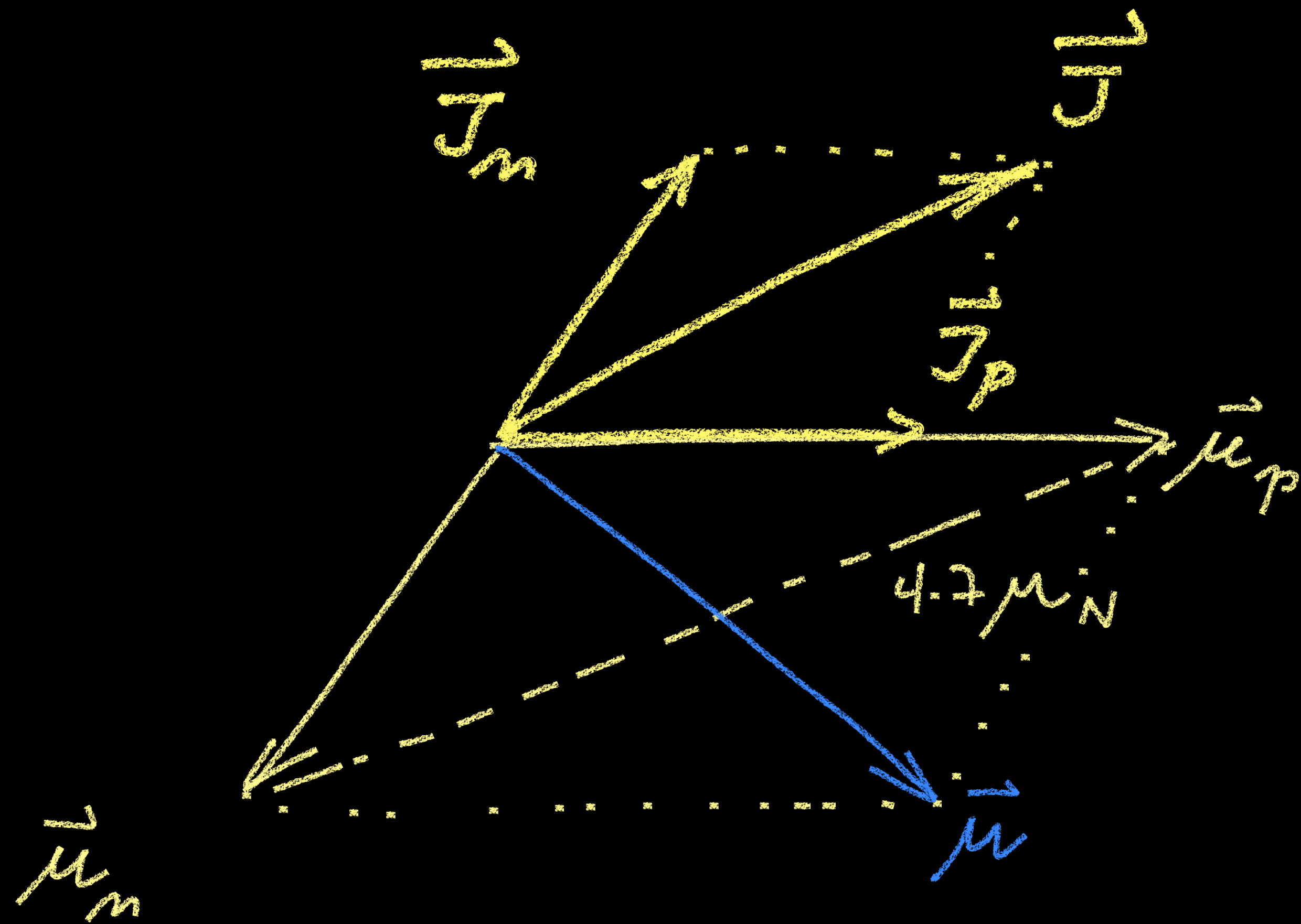
\* R. Rattazzi, comunicazioni private

# DUE PROBLEMI DA 'TUTA'

- I. Hadron compositness
- II. Rivelazione 'acustica' di materia oscura leggera

# I. HADRON COMPOSITENESS

# THE FORMATION OF DEUTERON



with  $l=0$



# THE FORMATION OF DEUTERON

With a non-relativistic calculation one obtains

$$\sigma = \frac{6.5 \times 10^4 \text{ barn}}{[v(\text{cm/sec})]}$$

Extrapolating to high velocities we see that we might roughly expect a  $\sigma \approx \mu\text{barn}$  for  $O(1)\sim\text{GeV}$  neutrons

But neutrons and protons in the final state of a LHC collision *comove* with pions

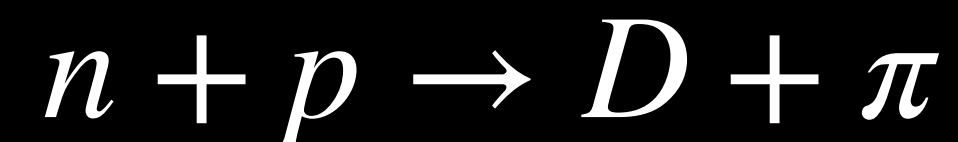


# COMOVING PIONS

Collisions with them might decrease the relative c.o.m. momentum of the  $np$  pair allowing a (non-radiative) formation of the bound state



This process competes and likely, *due to the  $\pi$  multiplicity*, overwhelms the pion radiation

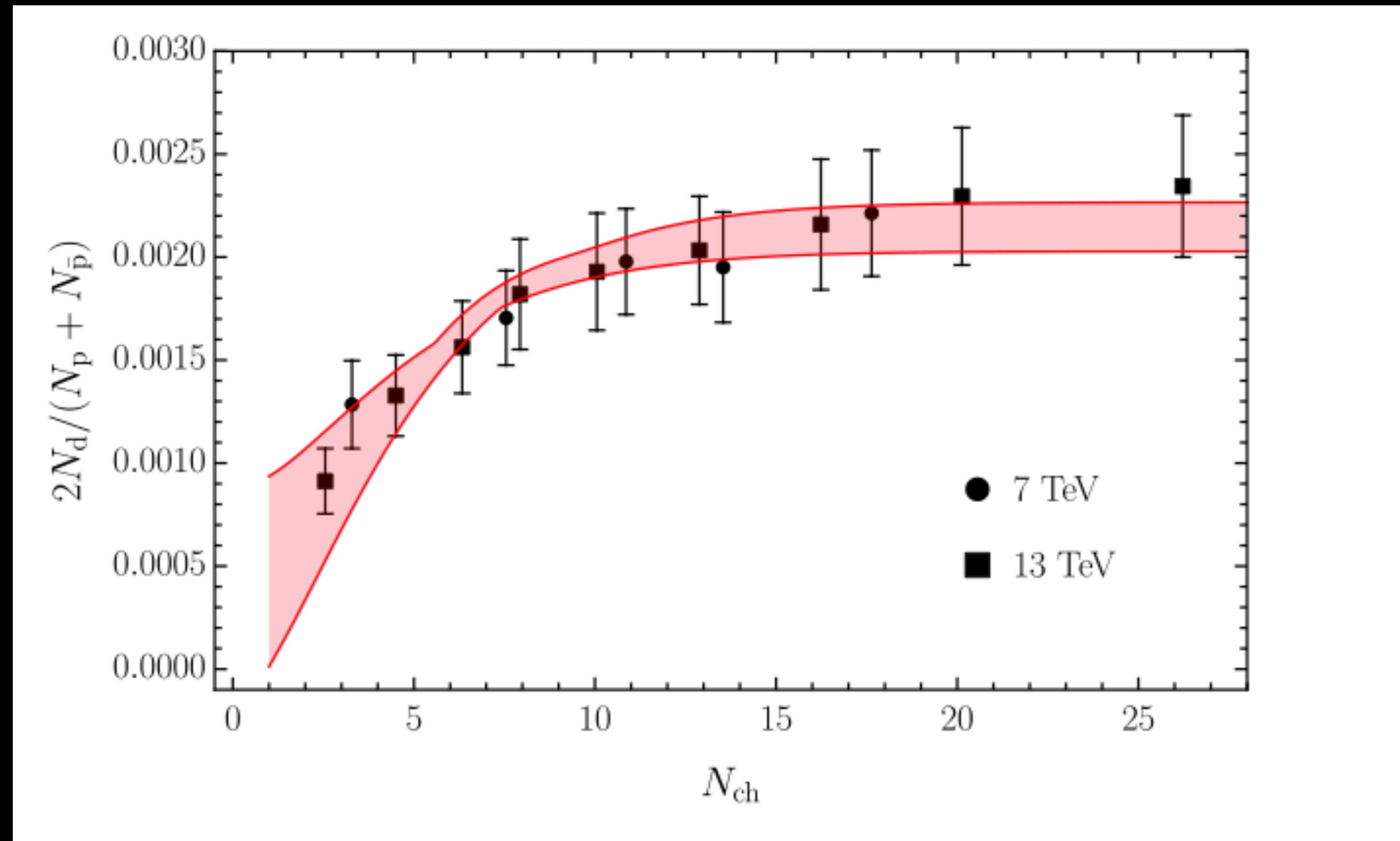


Proposed in F. Piccinini, A. Esposito, A. Pilloni and ADP, J. Mod. Phys 4 (2013) 1569

A. Guerrieri, F. Piccinini, A. Pilloni and ADP, Phys. Rev D90 (2014), 3, 032003

# DATA ON DEUTERONS VS MULTIPLICITY

Data for testing this idea came 7 years later...



**Not a fit!** (except for overall norm.)  
Parameters are taken from scattering data and distributions from Pythia.

S. Acharya et al. (ALICE), **Phys.Lett. B794, 50 (2019)**

A. Esposito, E. Gonzales-Ferreiro, A. Pilloni, ADP, C. Salgado, 2006.15044

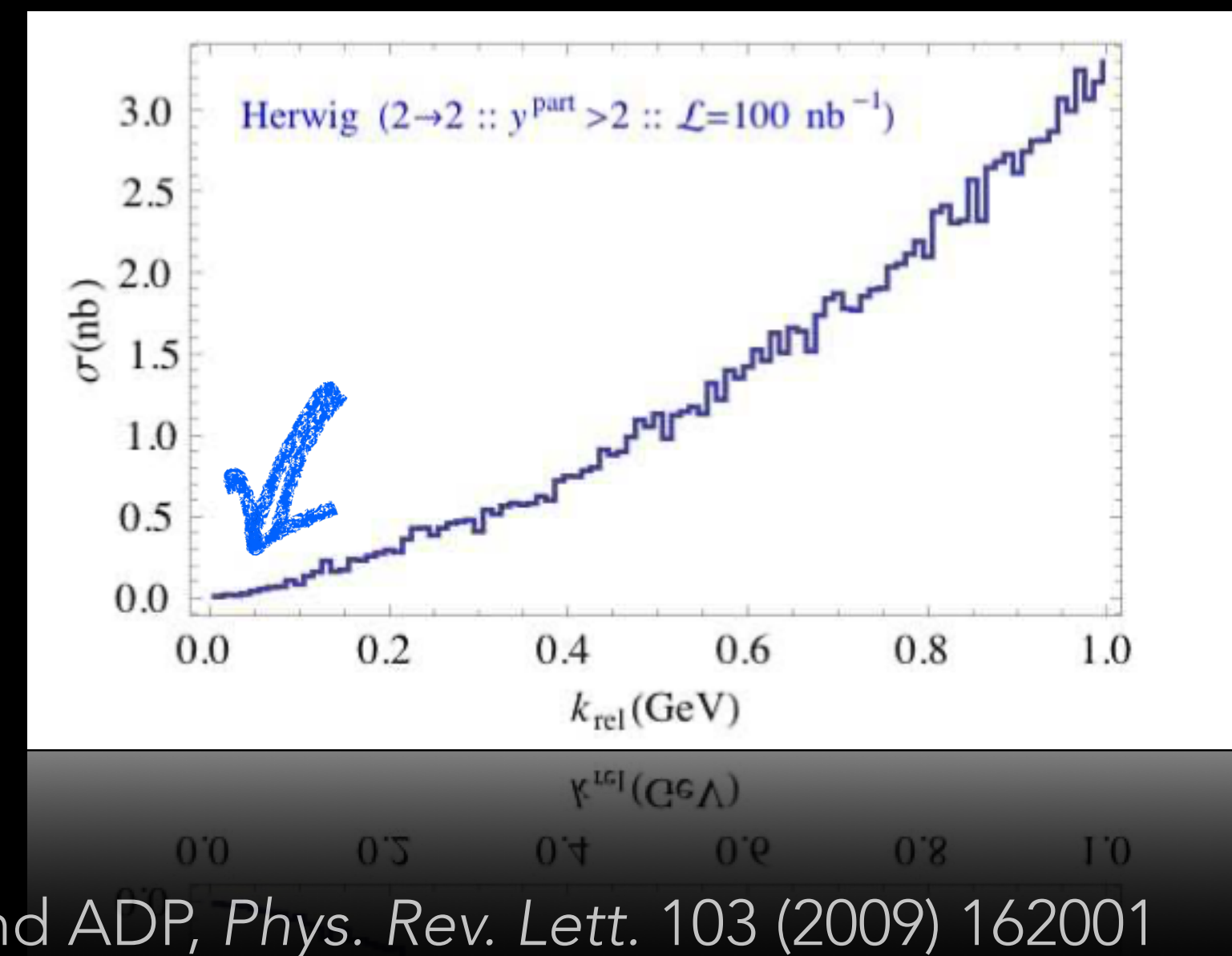
# THE COALESCENCE MOMENTUM

The basic idea in the previous calculation is that, to form the deuteron, the relative momentum in the  $pn$  pair must be **small**. This was originally done for the  $X(3872)^*$

$$p_D \approx 100 \text{ MeV}$$

$$p_X \approx 20 \text{ MeV}$$

(Would be a superloose  $D\bar{D}^*$  molecule, with  $B < 0.1 \text{ MeV}$ )



\* C. Bignamini, B. Grinstein, F. Piccinini and ADP, *Phys. Rev. Lett.* 103 (2009) 162001



# X(3872)

DISCOVERED BY BELLE IN 2003

CONFIRMED BY BaBar, DΦ, CDF, CMS, LHCb & ATLAS!

4  $pp \rightarrow X(3872) @ CMS$

4 Measurement of the cross section ratio

PROMPT PRODUCTION

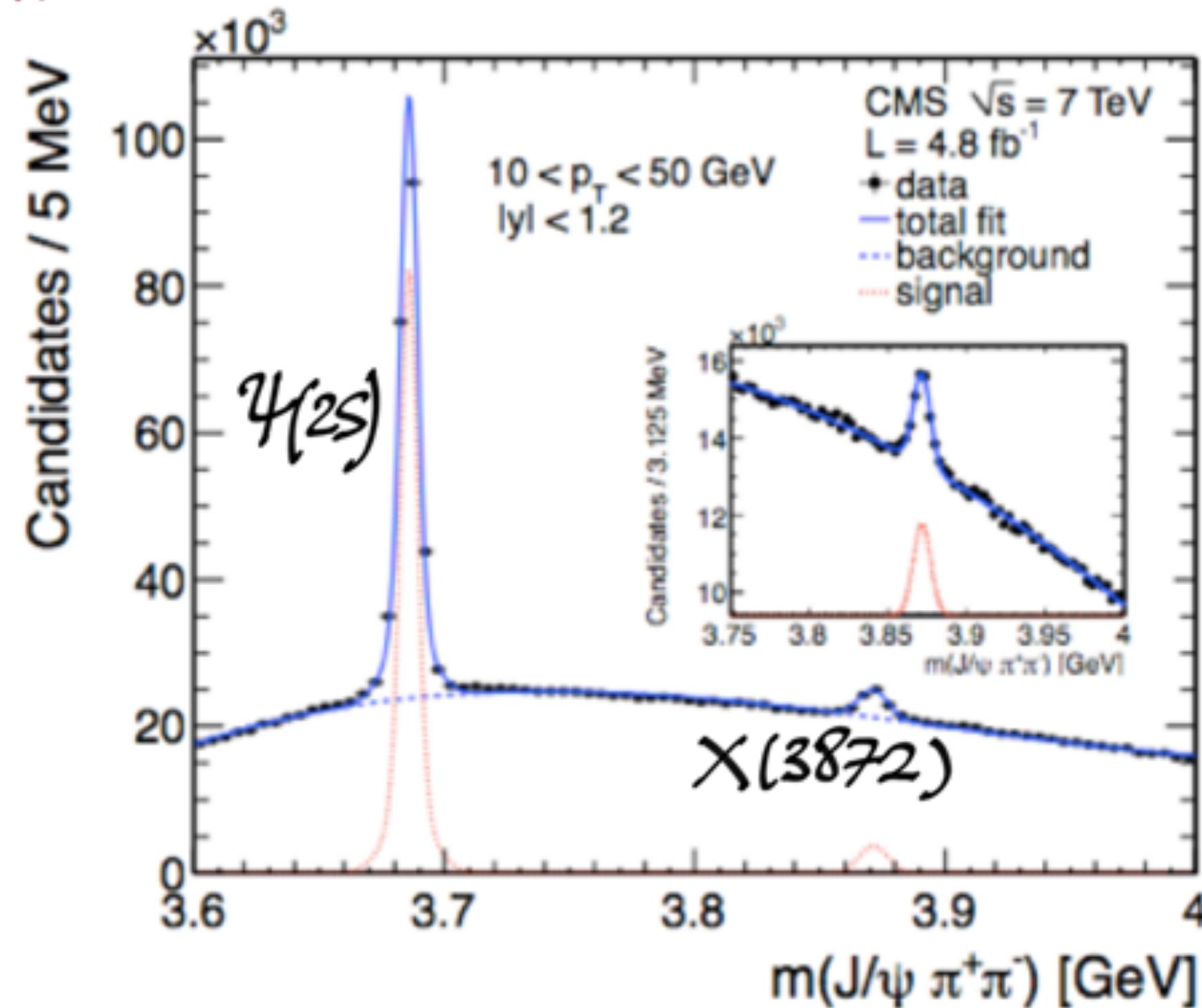
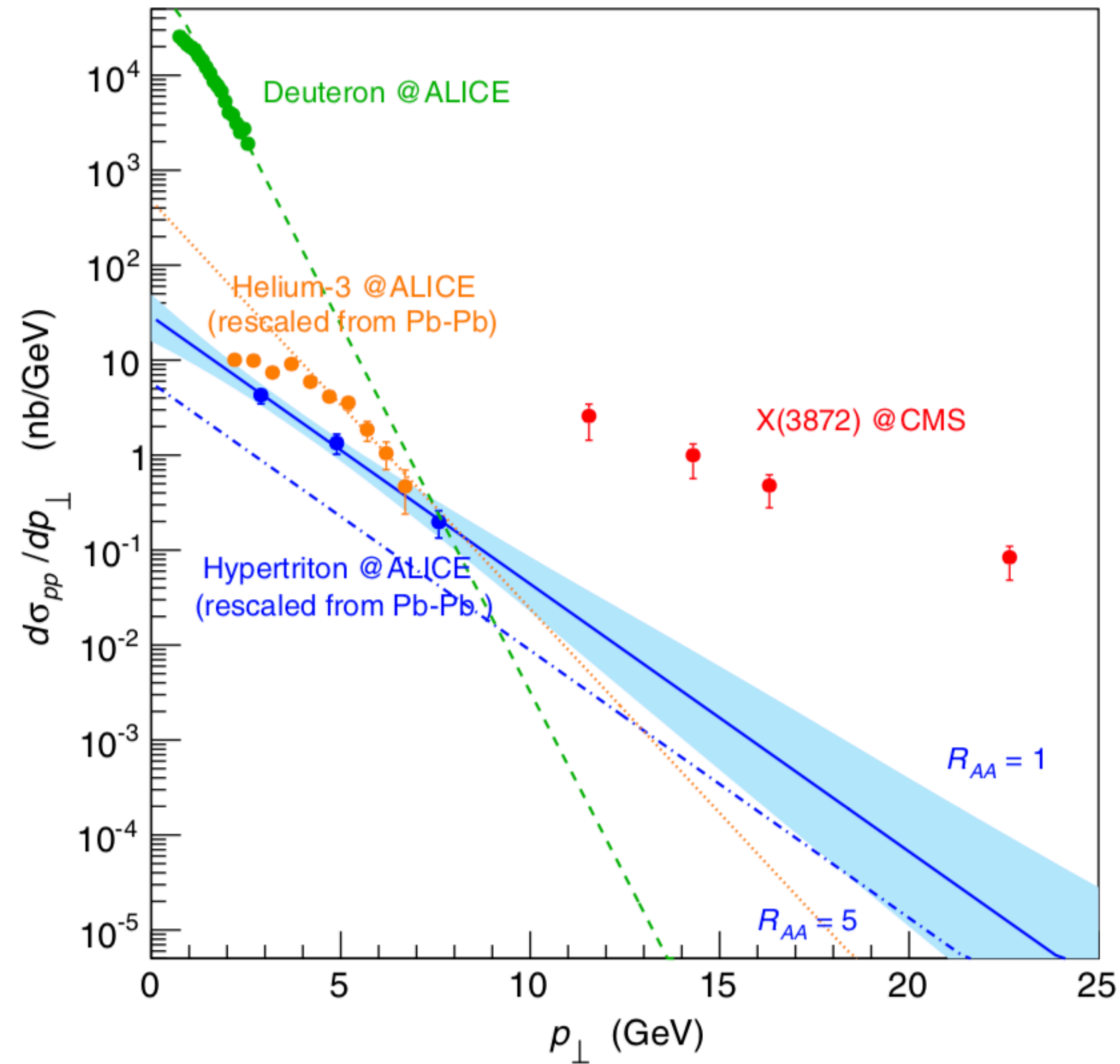


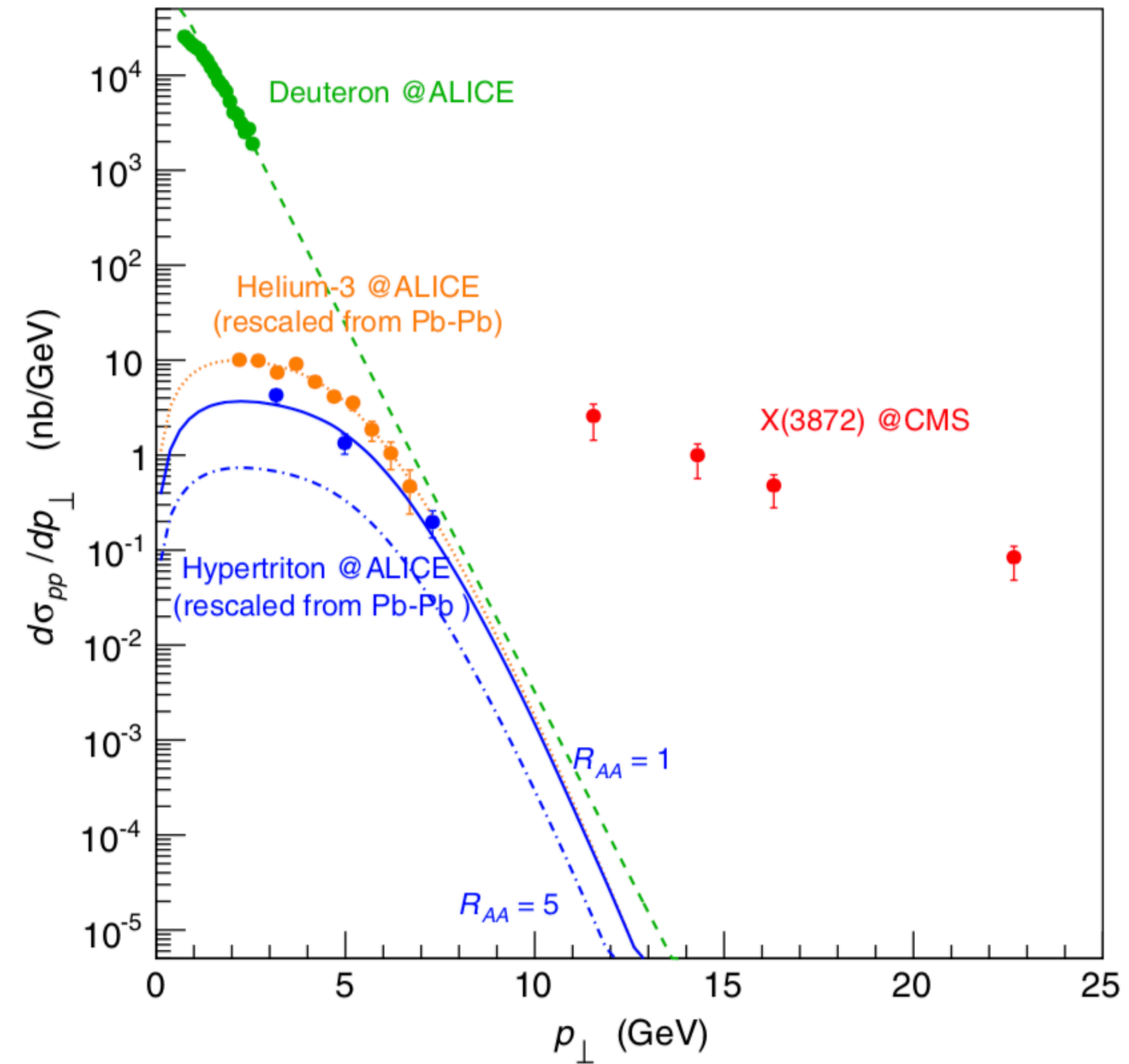
Figure 1: The  $J/\psi \pi^+ \pi^-$  invariant-mass spectrum for  $10 < p_T < 50$  GeV and  $|y| < 1.2$ . The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the  $X(3872)$  mass region.

# COLLISIONS AT HIGH PT

OBSERVATION OF LIGHT NUCLEI AT ALICE AND THE ...



PHYSICAL REVIEW D **92**, 034028 (2015)



Esposito, Guerrieri, Maiani, Piccinini, Pilloni, ADP, V. Riquer. PRD92 (2015) 034028

Esposito, Grinstein, Maiani, Piccinini, Pilloni, ADP, Riquer, 1709.09631

# THE TOTAL WIDTH OF THE X

LHCb has recently published the analysis of 2012 data with a remarkable determination of the X(3872).

LHCb Collaboration, 2005.13419

From the abstract (...)

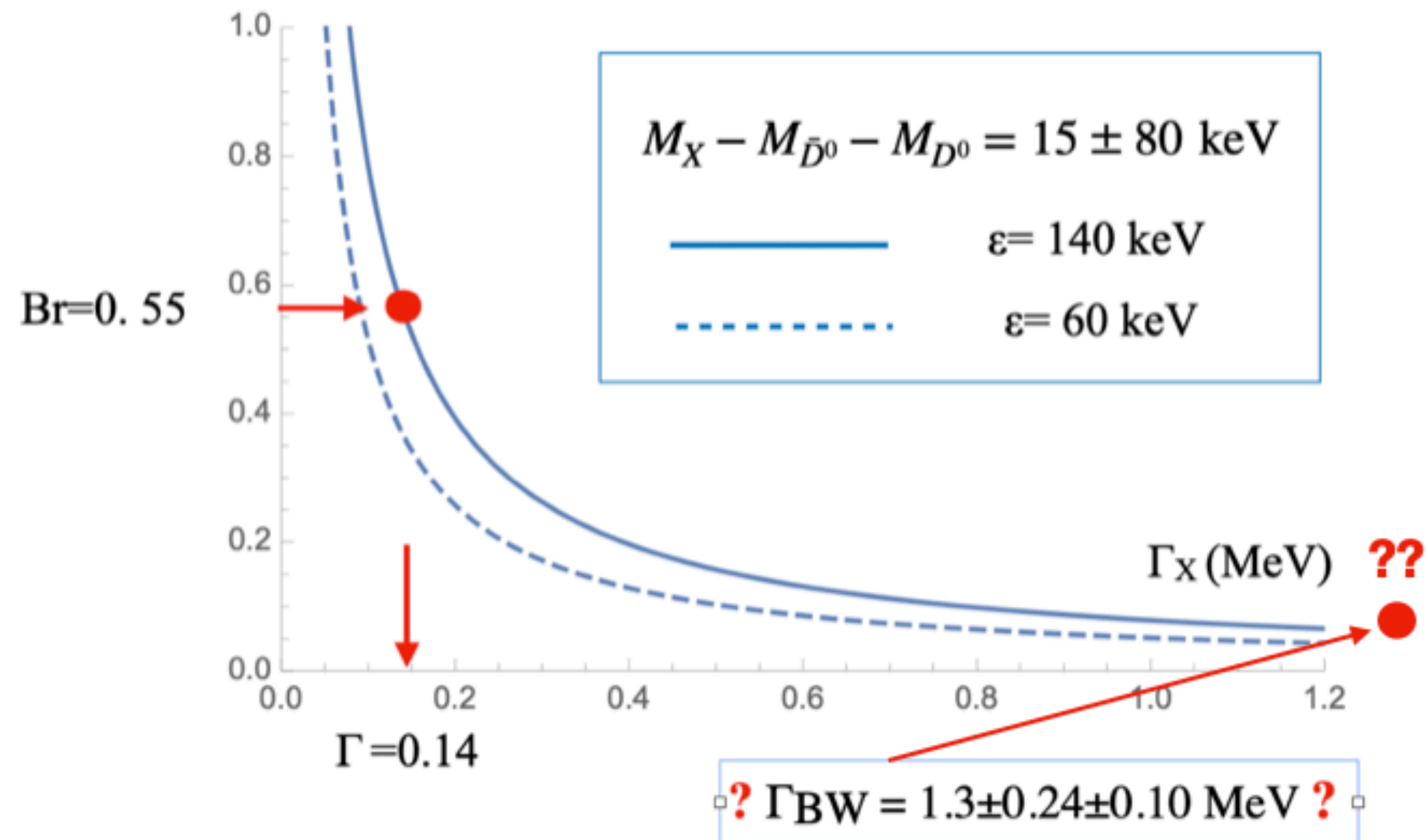
$$\Gamma = 1.39 \pm 0.24 \pm 0.10 \text{ MeV}$$



# The Landau-Weinberg test for X(3872)

see A. Polosa, Phys. Letters B 746 (2015) 248

$$\text{Br}(X \rightarrow \bar{D}^0 D^{*0} + \bar{D}^0 \bar{D}^{*0})$$



- Doesn't really look like....
- No prediction for  $\bar{g}$  in tetraquarks

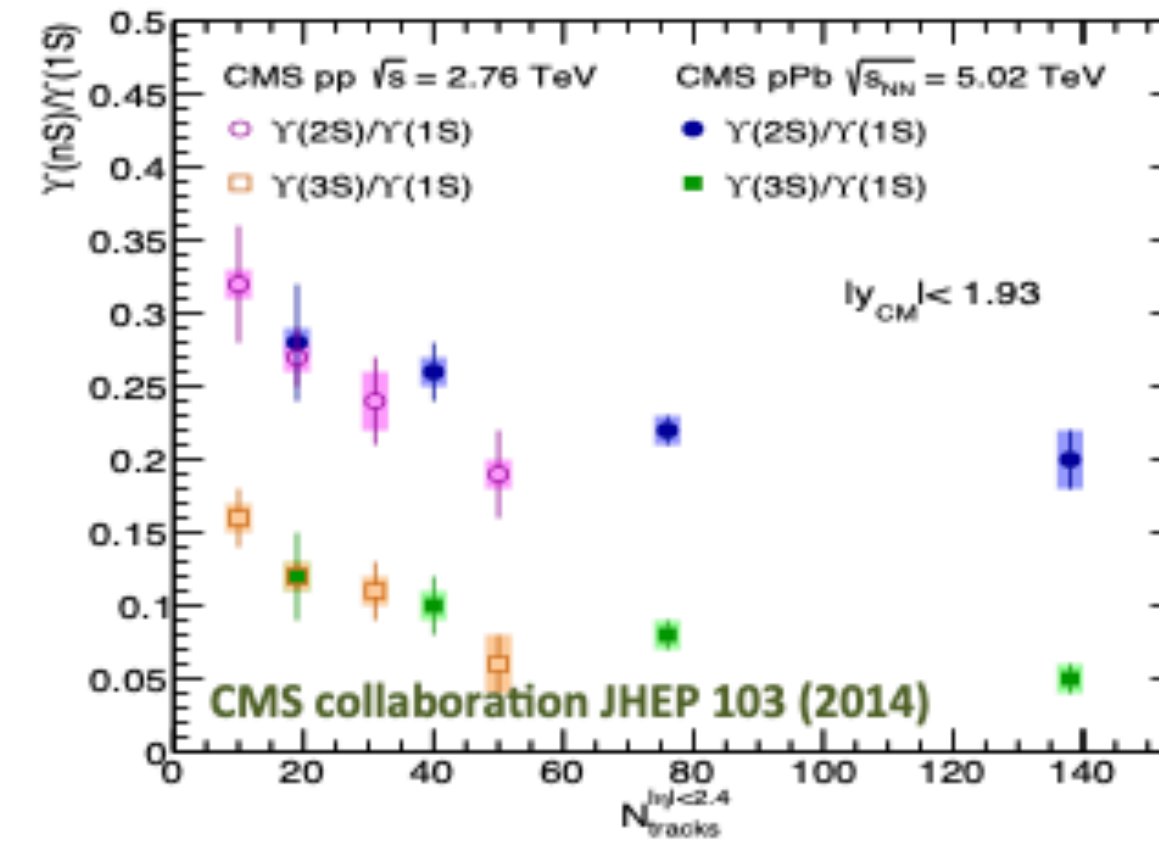
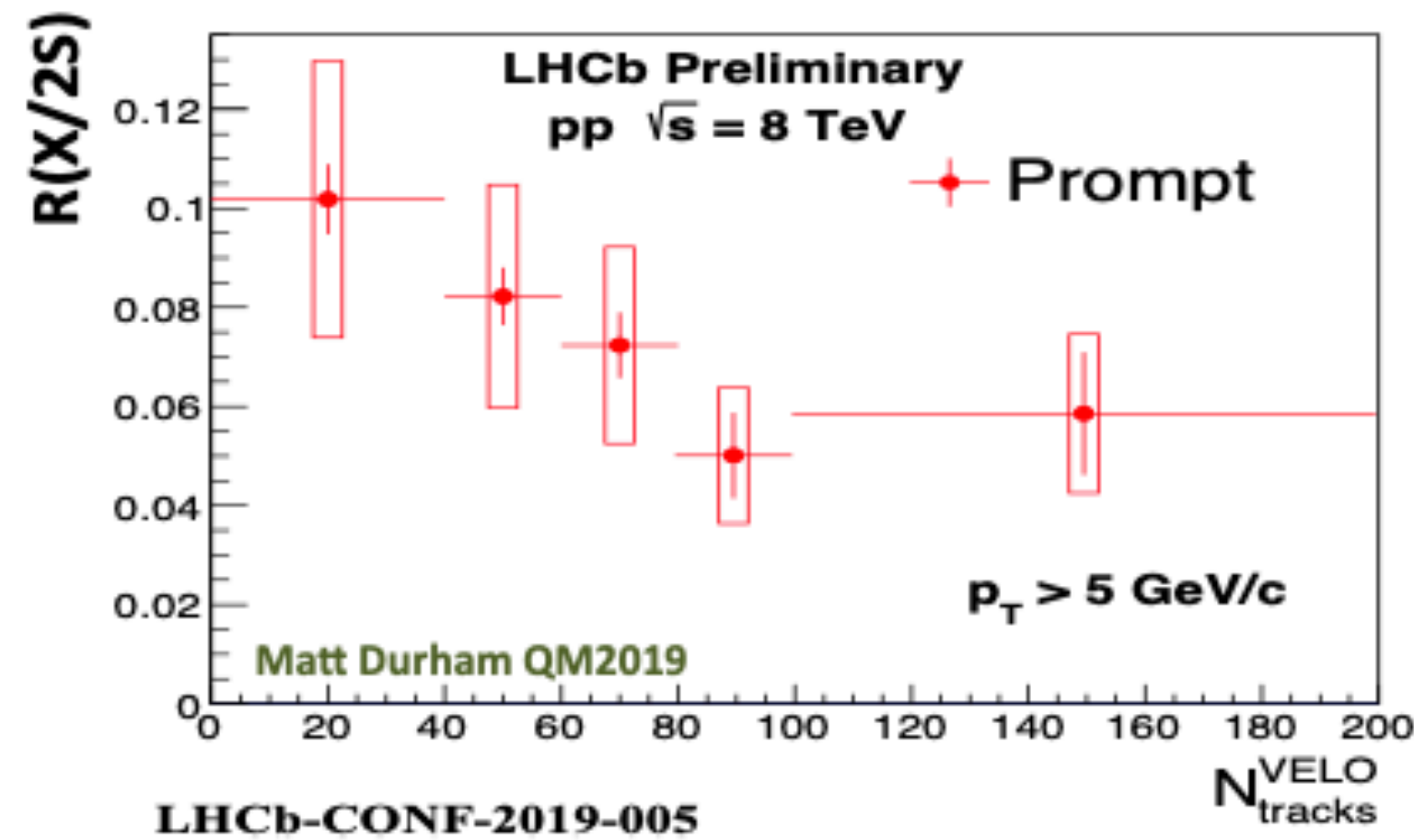


# New data from LHCb, CMS, ALICE on collider production of X & $\psi(2S)$ vs number of comovers

## The nature of the X(3872): comparison with $Y(nS)/Y(1S)$

Elena Ferreiro, Hard Probes 2020

- In fact, the effect found by LHCb is similar to the one previously found for Y by CMS



E. G. Ferreiro USC

Probing X(3872) structure via final state interactions 2

HP2020, 3/6/2020

- decrease of  $\text{Rate}(X)/\text{Rate}(\psi(2S))$  interpreted as “distruction of molecule” by collisions with comover particles;
- however, similar effect seen by CMS in the ratio  $\text{Rate}(Y(2S))/\text{Rate}(Y(1S))$  and by ALICE in  $\psi(2S)$  vs  $\psi(1S)$



#### 4. Summary and Outlook

We have found that the fraction of both  $\psi(2S)$  and  $\chi_{c1}(3872)$  which are produced promptly at the collision vertex decreases with increasing charged particle multiplicity in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The ratio of the prompt cross sections  $\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$  also decreases with multiplicity, while the ratio of cross sections from decays of  $B$  hadrons remains constant within uncertainties. This could indicate that promptly produced  $\psi(2S)$  and  $\chi_{c1}(3872)$  hadrons are being broken up via interactions with other particles produced in the event. These suppression more significantly affects the exotic  $\chi_{c1}(3872)$  than the conventional  $\psi(2S)$ , which may indicate that the  $\chi_{c1}(3872)$  has a smaller binding energy than the  $\psi(2S)$ . In this case, the  $\chi_{c1}(3872)$  may be a very weakly bound state, such as a hadronic molecule.

# THE PROMPT X(3872) AT LHCb

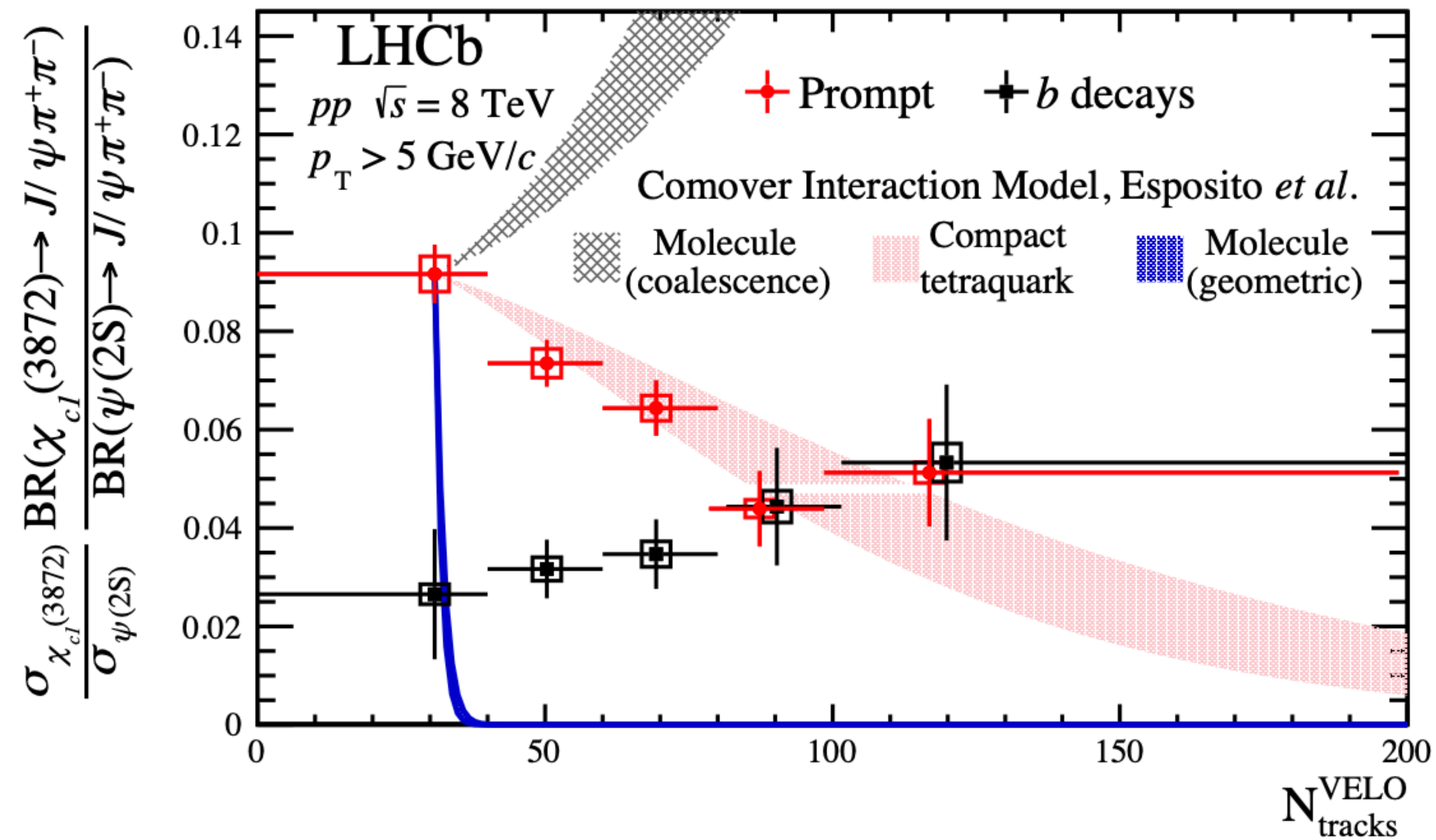


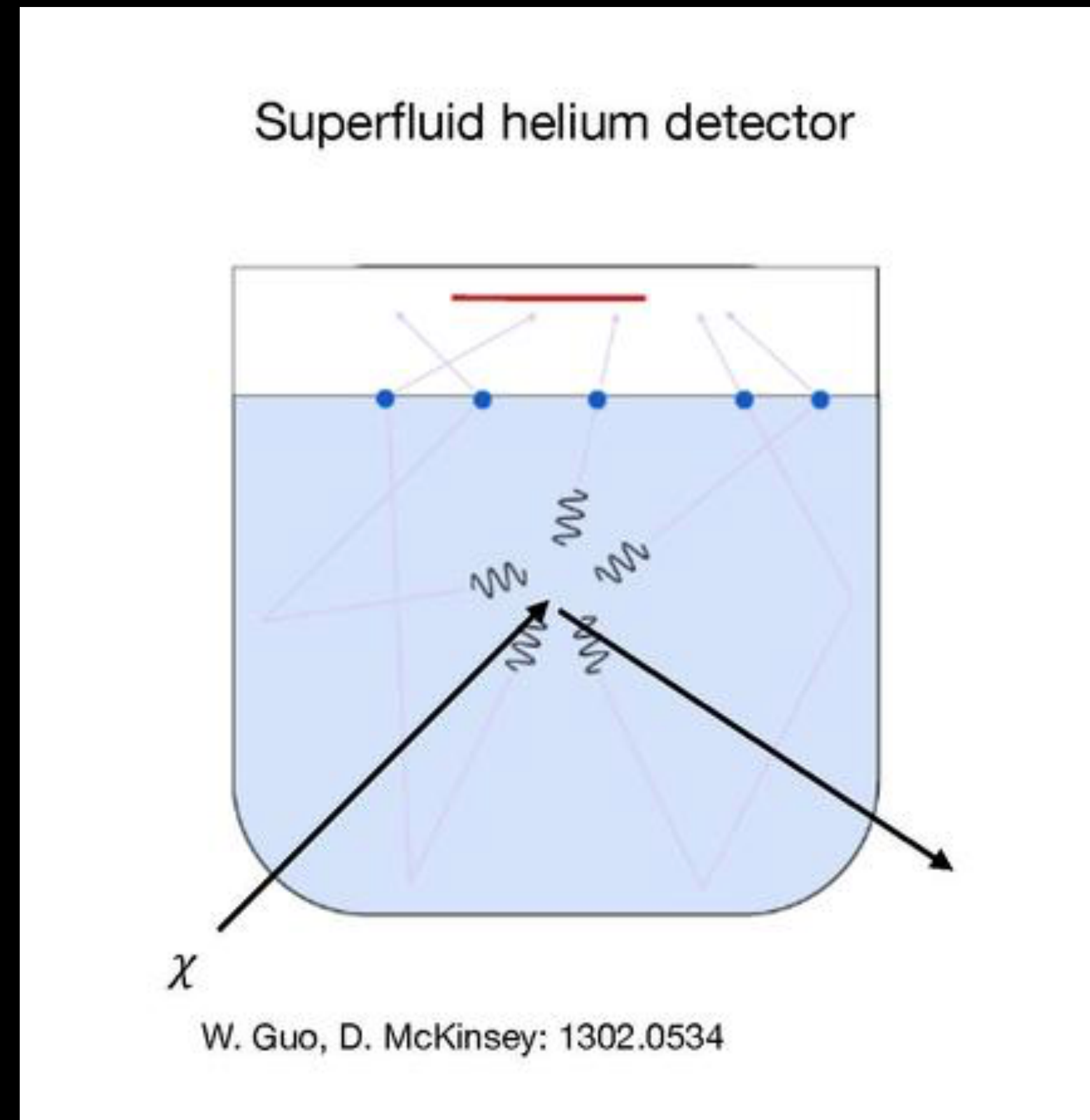
Figure 4: The ratio of the  $\chi_{c1}(3872)$  and  $\psi(2S)$  cross-sections measured in the  $J/\psi\pi^+\pi^-$  channel as a function of the number of tracks reconstructed in the VELO. The point-to-point uncorrelated (correlated) uncertainties are shown as vertical error bars (boxes) and the bin widths are shown as horizontal error bars. See text for details on calculations from Ref. [43]

## II. RIVELAZIONE ACUSTICA DI MATERIA OSCURA (SUB-MEV)

Una introduzione alla ricerca diretta di materia oscura con svariate tecnologie, è stata fornita nel precedente seminario di G. Cavoto



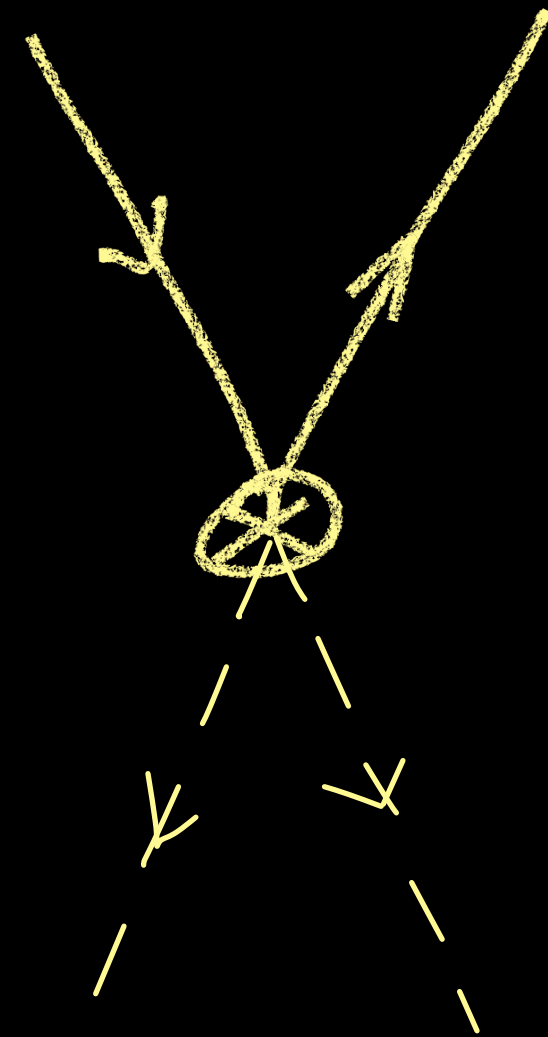
# KEV-MEV, LDM IN SUPERFLUID HE4



See also, Hertel, Biekert, Lin, Velan, McKinsey, 1810.06283; Maris, Seidel, Stein, PRL2017, 1706.00117

# PHONONS ECHOES

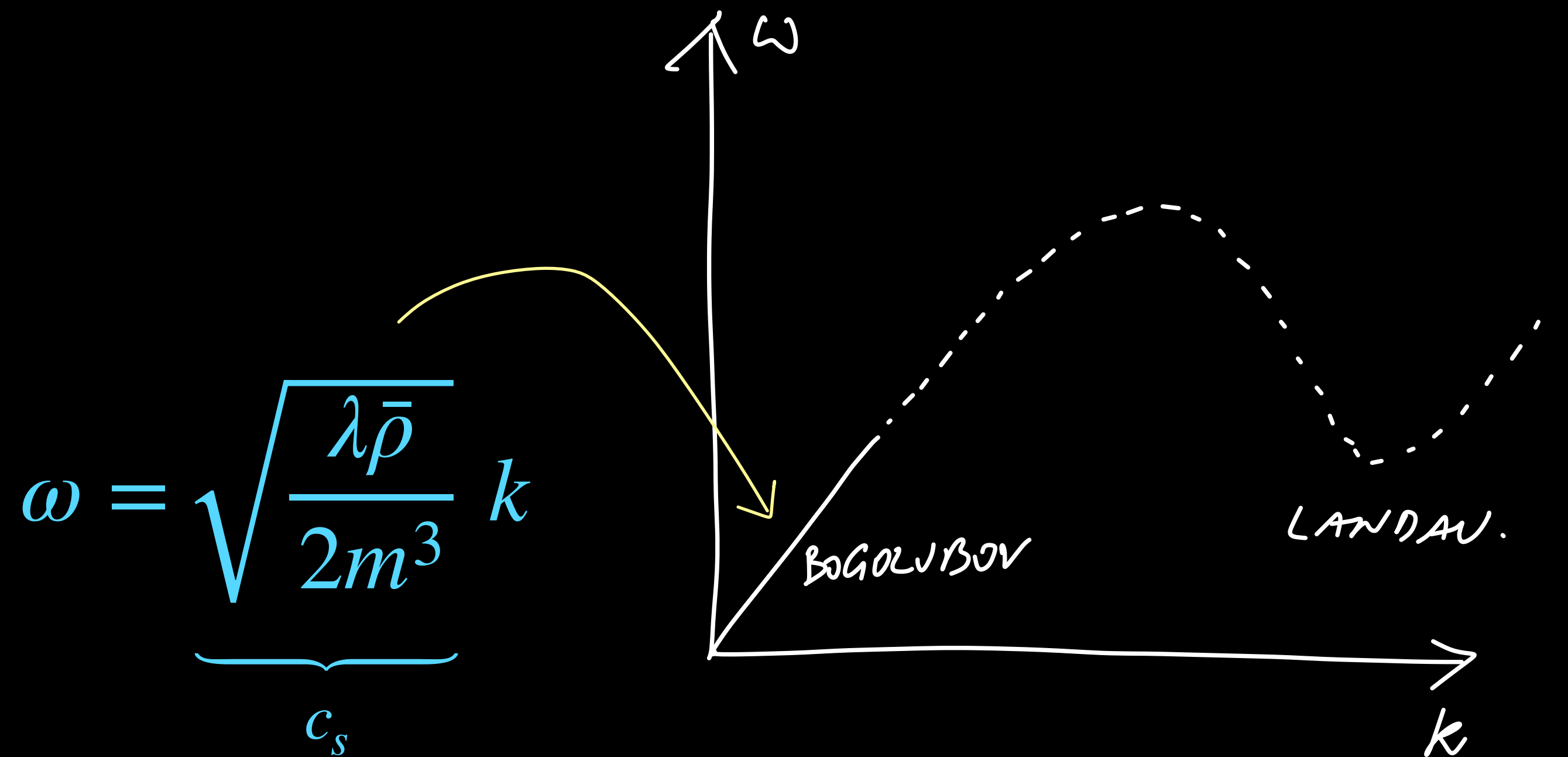
$$Q^2 = (p_{\chi, \text{ in}} - p_{\chi, \text{ out}})^2 < 0$$



$$Q^2 = ((\omega_1, \mathbf{k}_1) + (\omega_2, \mathbf{k}_2))^2$$

# PHONON ECHOES

$$Q^2 = ((\omega_1, \mathbf{k}_1) + (\omega_2, \mathbf{k}_2))^2$$



phonon 4-vectors are space-like

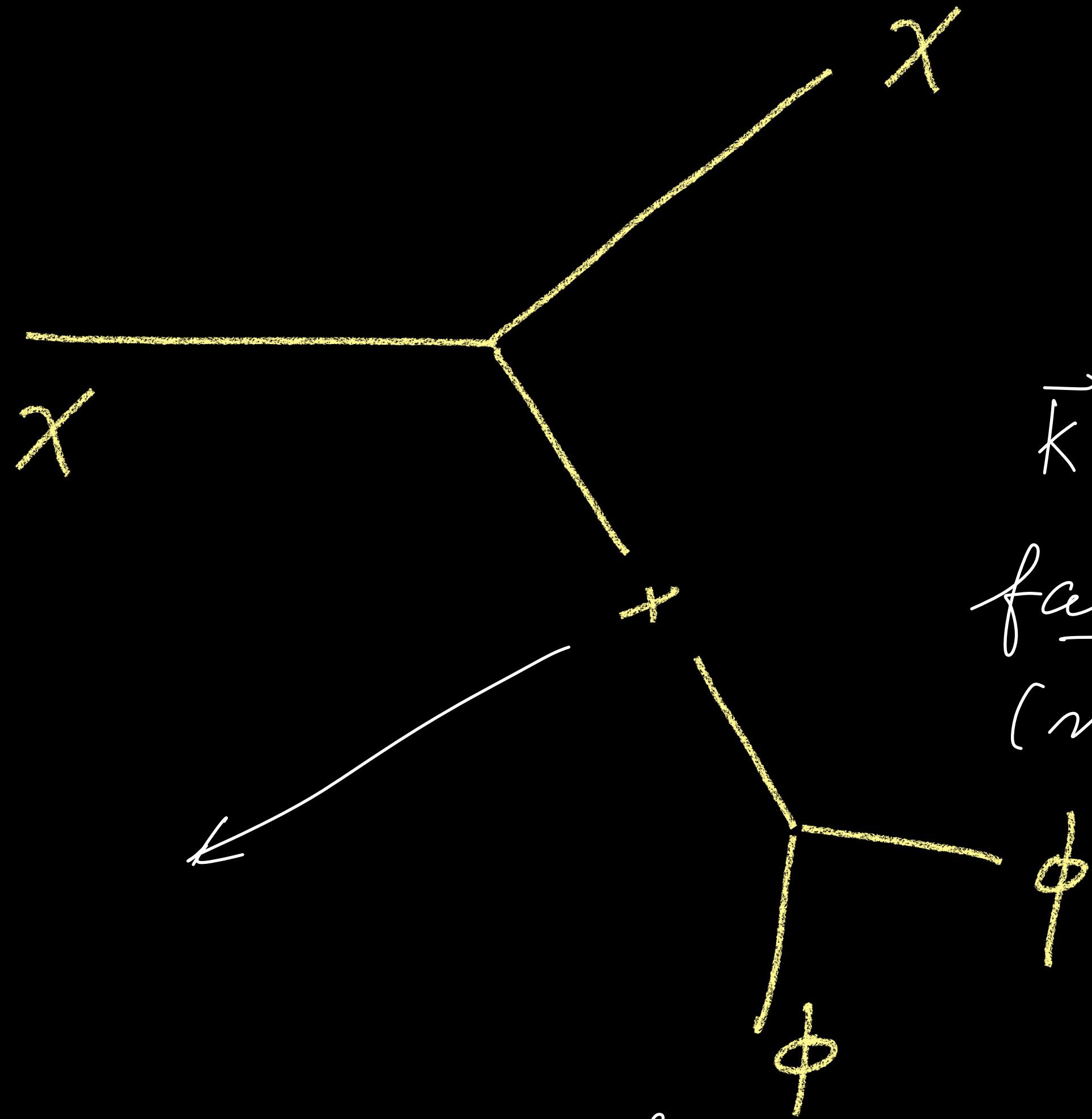
(Here the velocity  $c_s$  is a dimensionless number  $\sim 10^{-6}$ , measured in units of  $c=1$ )

# MASSLESS PHONONS?

$$(\omega, \mathbf{k}) \mapsto \begin{pmatrix} \omega \\ c_s \mathbf{k} \end{pmatrix}$$

$$\Delta(k) = \frac{i}{\omega^2 - c_s^2 \mathbf{k}^2 + i\epsilon} = \frac{i}{2\omega_1 \omega_2 (1 - \cos \theta) + i\epsilon}$$

# KINEMATICS



$\vec{k}$  is a phase space  
factorization momentum.  
 (not a (virtual) photon  
 momentum)

$$\left\{ \frac{1}{2\pi} \int_{S_1}^{S_2} ds \right.$$

$$S = Q^2 \quad \& \quad S_1 = - (P_x + P'_x)^2$$

$$S_2 = - (P_x - P'_x)^2$$

# PHONON ECHOES

$$Q^2 = ((\omega_1, \mathbf{k}_1) + (\omega_2, \mathbf{k}_2))^2$$

take  $\omega = \omega_1 + \omega_2$  and  $\mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2$

$$Q^2 = \omega^2 - \mathbf{k}^2 \simeq -\frac{\omega_1^2}{c_s^2} - \frac{\omega_2^2}{c_s^2} - \frac{2\omega_1\omega_2}{c_s^2} \cos \theta < 0$$

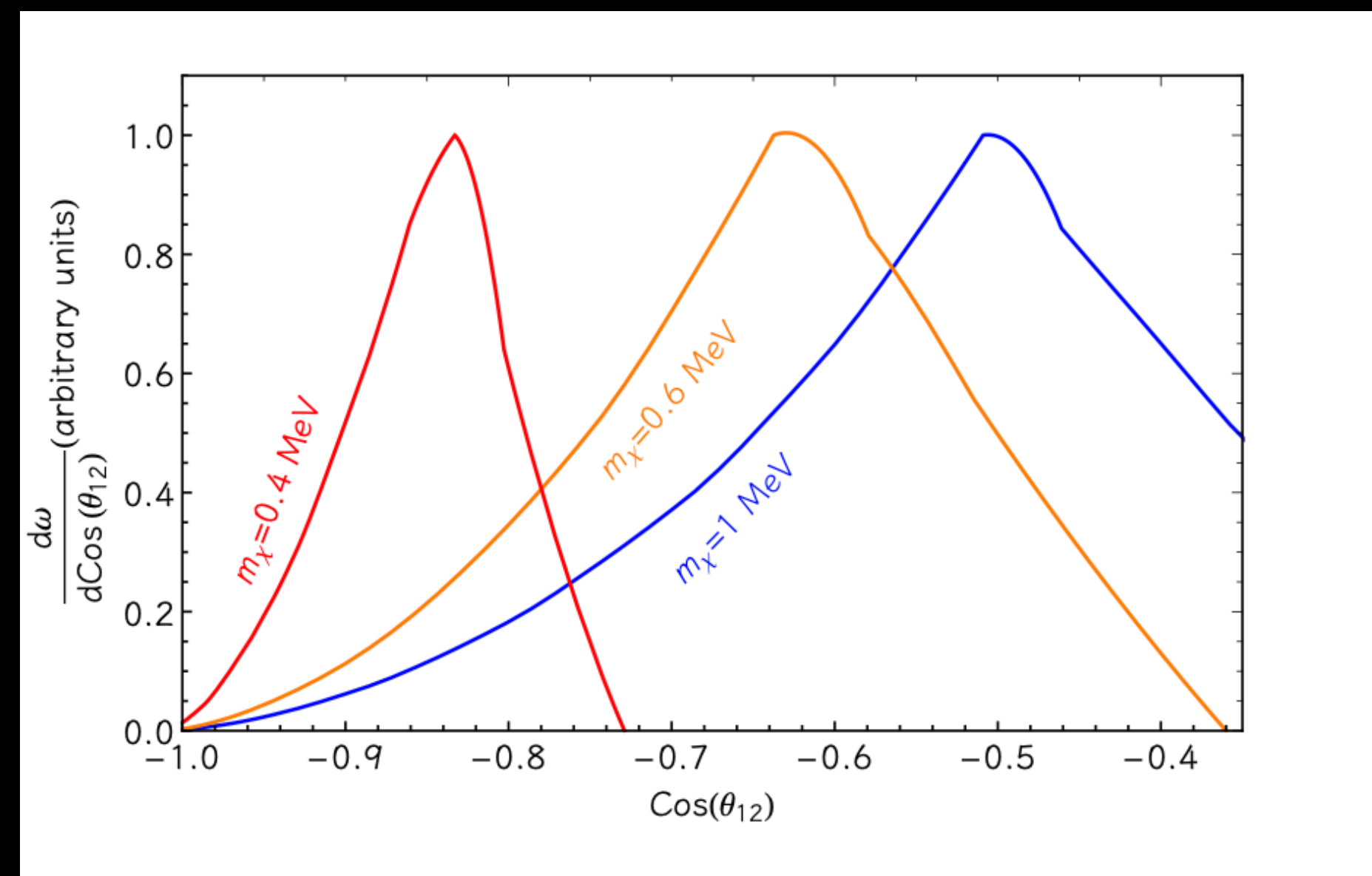
instead of  $\omega^2 - c_s^2 \mathbf{k}^2$  — that is *like* a *supersonic* phonon which branches into two 'sound-like' phonos. Treat it as a tachyon

$$\omega = \sqrt{\mathbf{k}^2 + Q^2} = c_s |\mathbf{k}_1| + c_s |\mathbf{k} - \mathbf{k}_1| \quad \text{w/ } \mathbf{k}^2 > -Q^2$$

# PHONON ECHOES

$$\omega = \sqrt{\mathbf{k}^2 + Q^2} = c_s |\mathbf{k}_1| + c_s |\mathbf{k} - \mathbf{k}_1| \quad \text{w/ } \mathbf{k}^2 > -Q^2$$

Back-to-back phonons ( $\mathbf{k} \rightarrow 0$ ) are possible only for very light dark matter ( $Q^2 \rightarrow 0$  — take the NR limit for dm)



# PHONON ECHOES

Indeed the max. momentum transfer (NR) is  $2m_\chi v_\chi$ , which is very low for light dm. That means ( $\approx$ back-to-back)

$$|\mathbf{k}_1 + \mathbf{k}_2| < 2m_\chi v_\chi$$

but still each  $\omega_{1,2} = c_s k_{1,2}$  can be *large enough* to allow detection. The max. energy of the single phonon is instead

$$c_s \times 2m_\chi v_\chi$$

(need for observation  $\gtrsim 0.62$  meV or  $m_\chi \gtrsim 1$  MeV)



# SINGLE PHONON


$$\mathbf{p}_\chi = \mathbf{p}'_\chi + \mathbf{k}$$

$$\frac{\mathbf{p}_\chi^2}{2m_\chi} = \frac{\mathbf{p}'_\chi{}^2}{2m_\chi} + c_s |\mathbf{k}|$$

$$\left( \cos \theta - \frac{c_s}{v_\chi} - \frac{k}{2m_\chi v_\chi} \right) = 0$$

A preferred (Cherenkhov) angle of emission

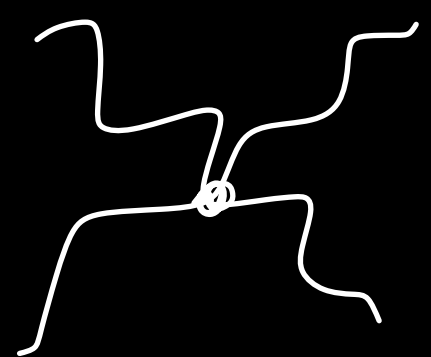
# FEYNMAN RULES



$$\frac{i}{\omega^2 - c_s^2 \vec{k}^2 + i\epsilon}$$



$$g_1(\omega_1 \vec{k}_2 \cdot \vec{k}_3 + \text{cyclic}) + g_2 \omega_1 \omega_2 \omega_3$$



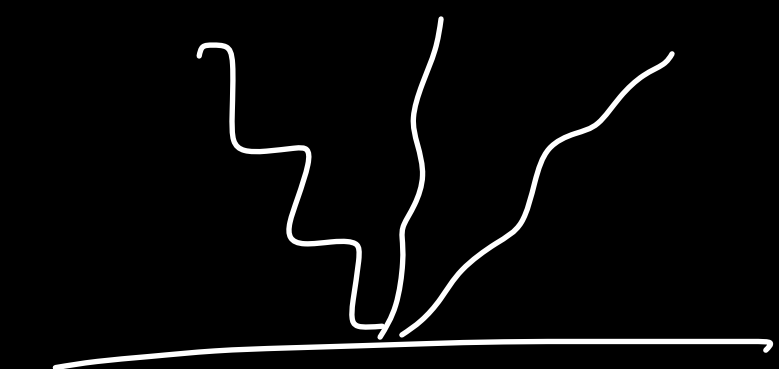
$$i\lambda_1 (\vec{k}_1 \cdot \vec{k}_2 \vec{k}_3 \cdot \vec{k}_4 + (13) + (23)) + i\lambda_2 (\omega_1 \omega_2 \vec{k}_3 \cdot \vec{k}_4 + (13) + (14) + (24) + (34)) + i\lambda_3 \omega_1 \omega_2 \omega_3 \omega_4$$

where  $g_1, g_2, \lambda_1, \lambda_2, \lambda_3$  are related to the thermodyn. quantities of He.

# FEYNMAN RULES (WITH DARK MATTER)

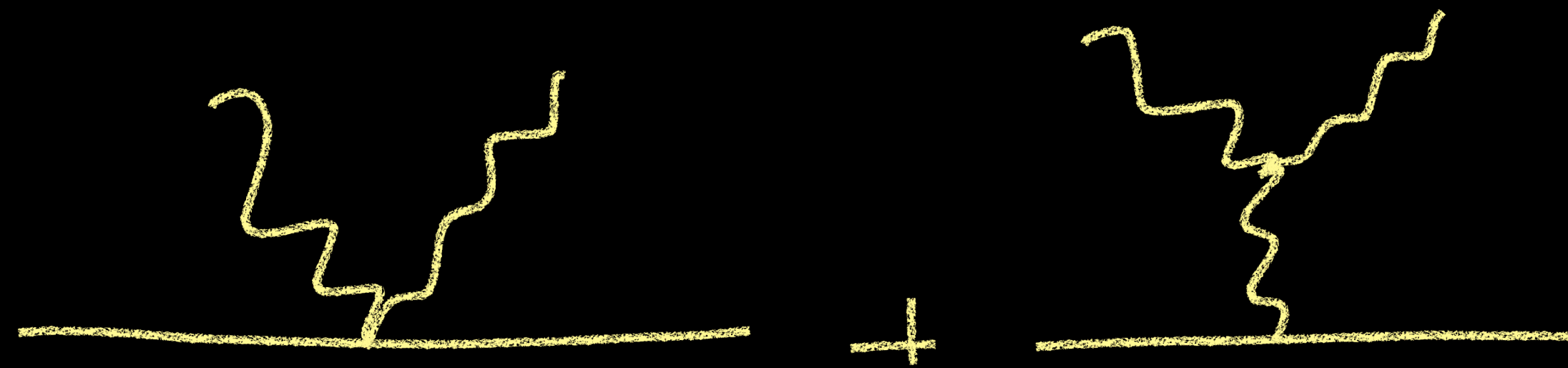

$$g_1 \omega$$


$$i g_2 \vec{q}_1 \cdot \vec{q}_2 + i g_3 \omega_1 \omega_2$$


$$g_4 \left( \omega_1 \overbrace{\vec{q}_2 \cdot \vec{q}_3} + (13) + (12) \right) + g_5 \omega_1 \omega_2 \omega_3$$

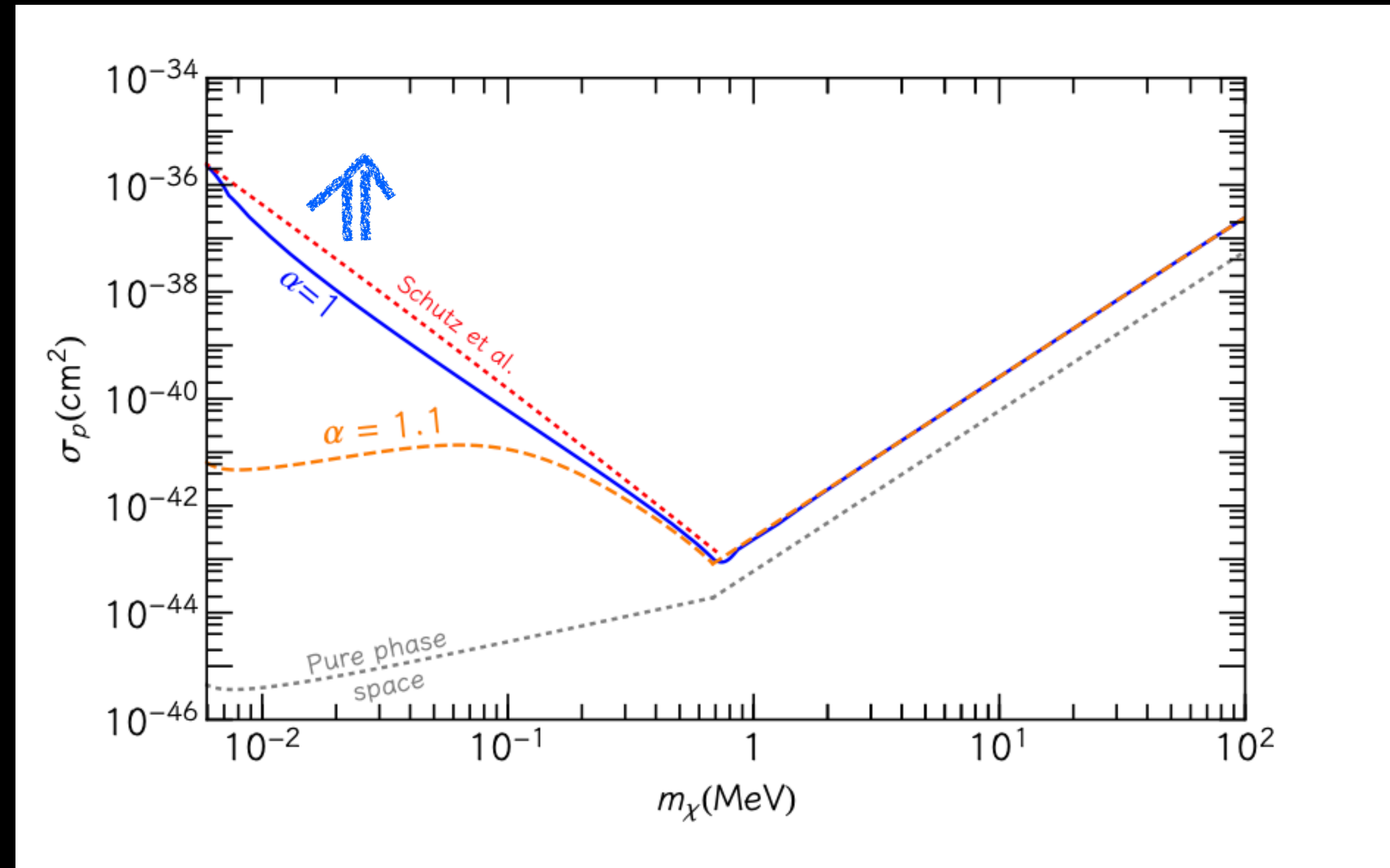
# A LITTLE THEOREM

The back-to-back limit is kinematically reachable at very low  $dm$  mass. But what happens to the cross section?



A (partial) cancellation between these two diagrams sets in!

# A LITTLE THEOREM: A DIAGRAMMATIC EXPLANATION OF THE EXCLUSION PLOT

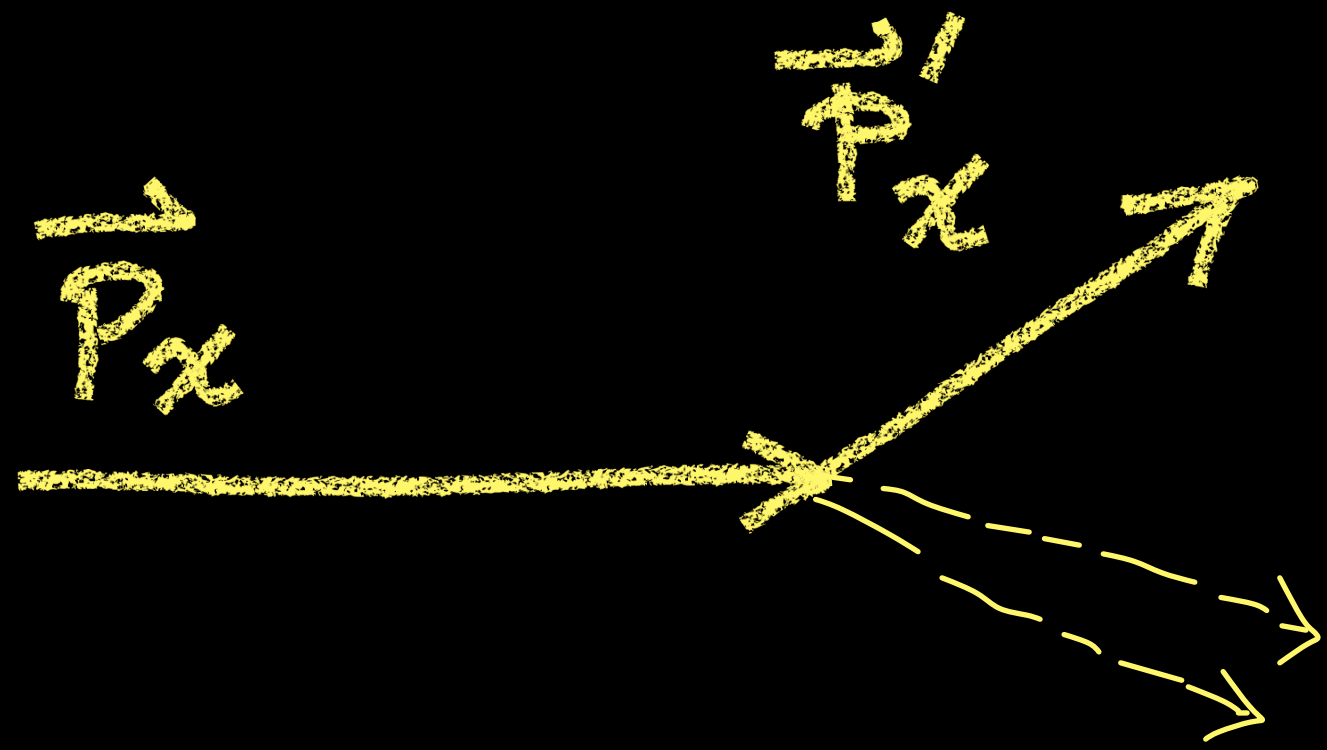


Excluded region corresponding to 3/evts/Kg/year @ zero bckg. Impose total energy released  $>1\text{meV}$

A. Caputo, A. Esposito, ADP, PRD 100 (2019) 116007

K. Schutz, K.M. Zurek, PRL (2016), 117 and S. Knapen, T. Lin, K.M. Zurek, PRD95 (2017) 056019

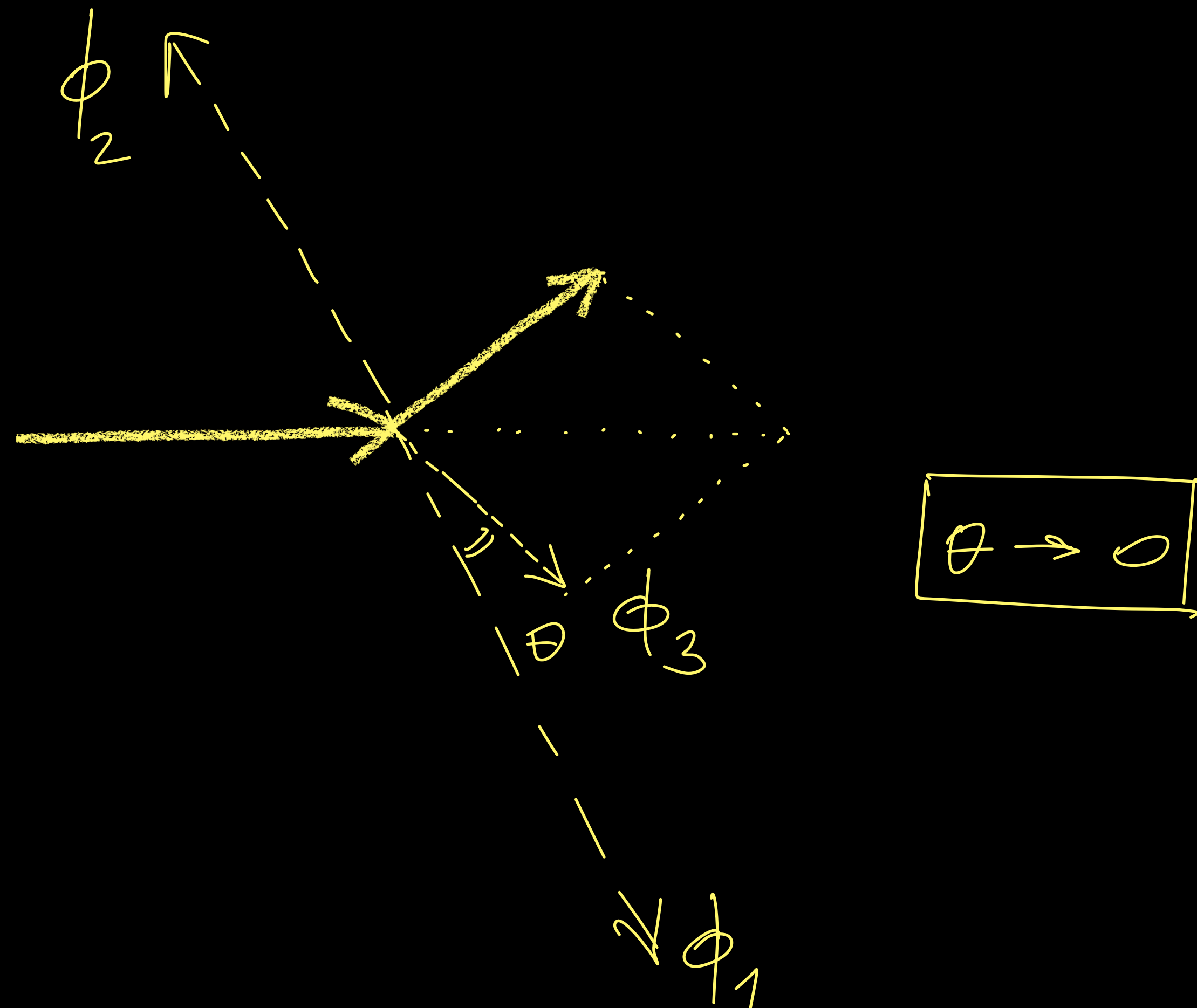
# THREE PHONONS



$\approx$  collinear, but soft!  
(suppressed by powers of  $g$   
in the EFT)

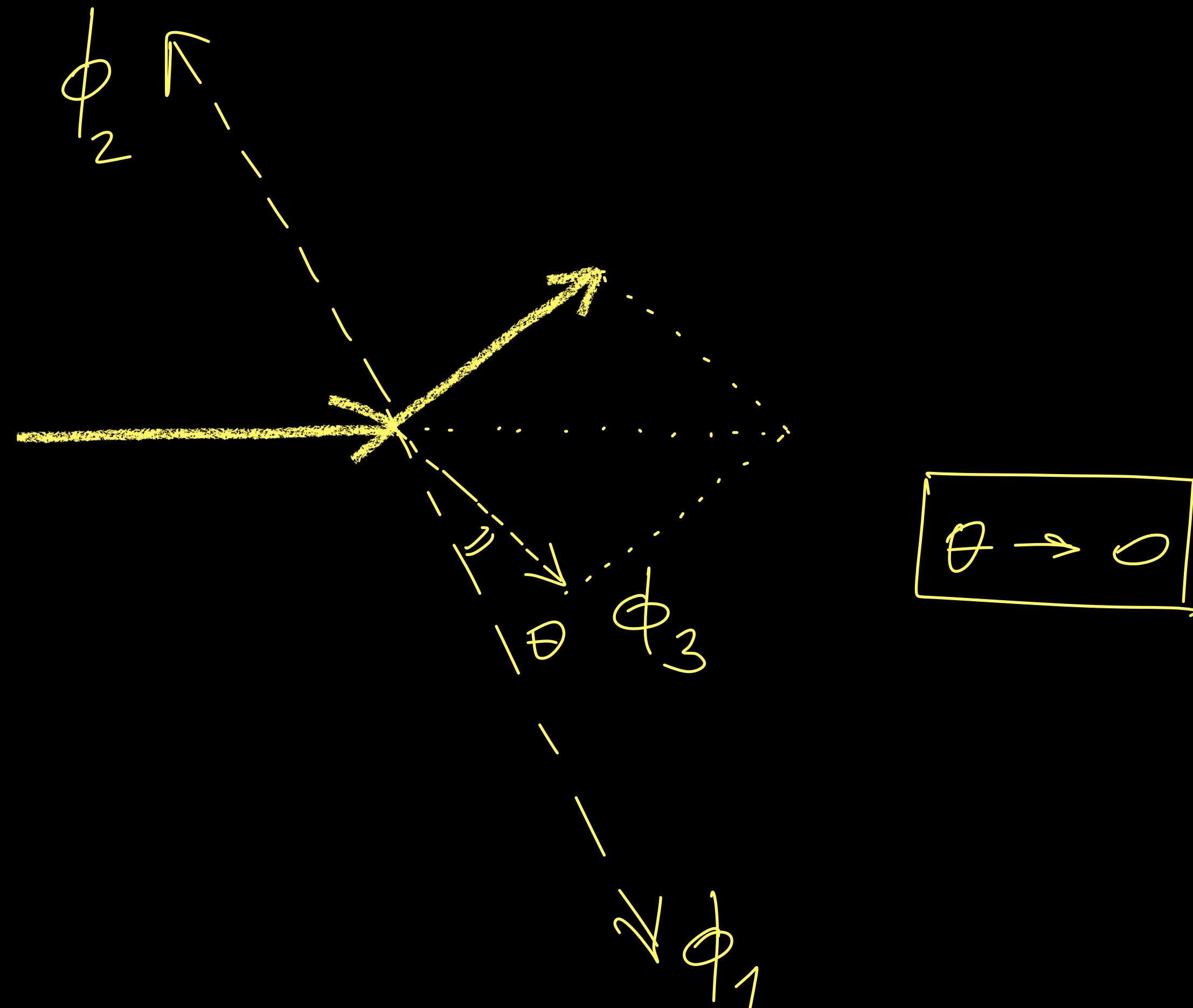
# THREE PHONONS

What if two phonons are produced but one of them gets missed?



# THREE PHONONS

We found a collinear divergence which can't be overridden by soft phonons matrix elements





# TO CANCEL THE DIVERGENCE

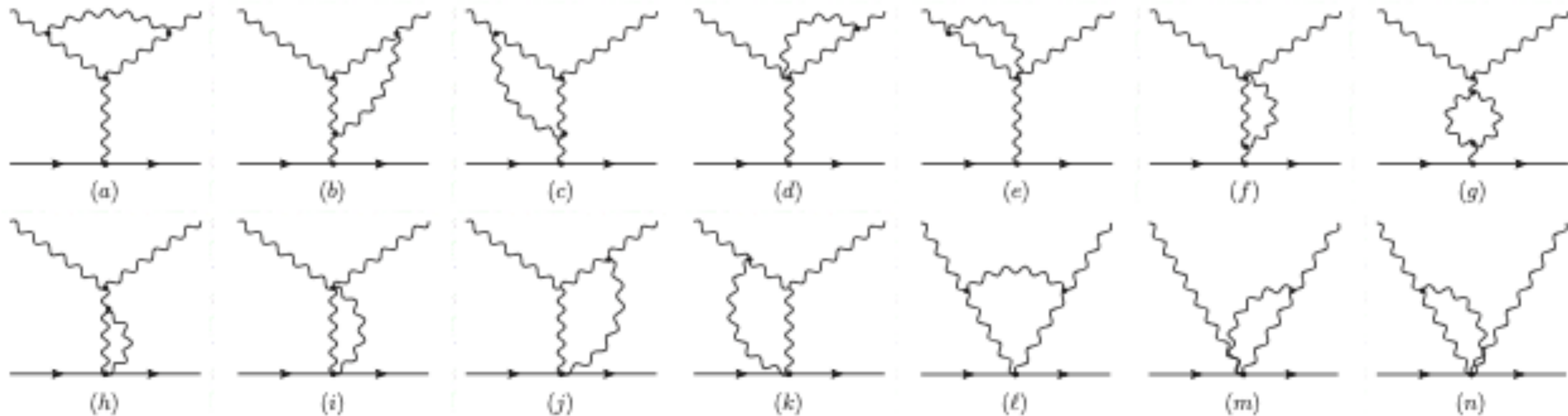


FIG. 1. Virtual corrections to the two-photon emission diagrams.

# CONCLUSIONI

Sfortunatamente attese di 40 anni, sono troppo per me e per molti dei miei ~coetanei. (Anche 30, 20, 10, tic toc...)

1. Mi piacerebbe convincere gli sperimentali più bravi a fare spettroscopia esotica. Penso che questo potrebbe *stravolgere*, rapidamente, la faccia del campo.
2. Starei molto attento a far fare le carriere solo su cose considerate di moda. Le mode vanno bene ma bisogna sapersi fermare ogni tanto.
3. Risusciterei la fisica del freddo (superfluidità) per realizzare prototipi con cui studiare i fenomeni menzionati. Necessaria la cooperazione con specialisti di TES e sensori bolometrici. [+ Vedi talk di Cavoto].